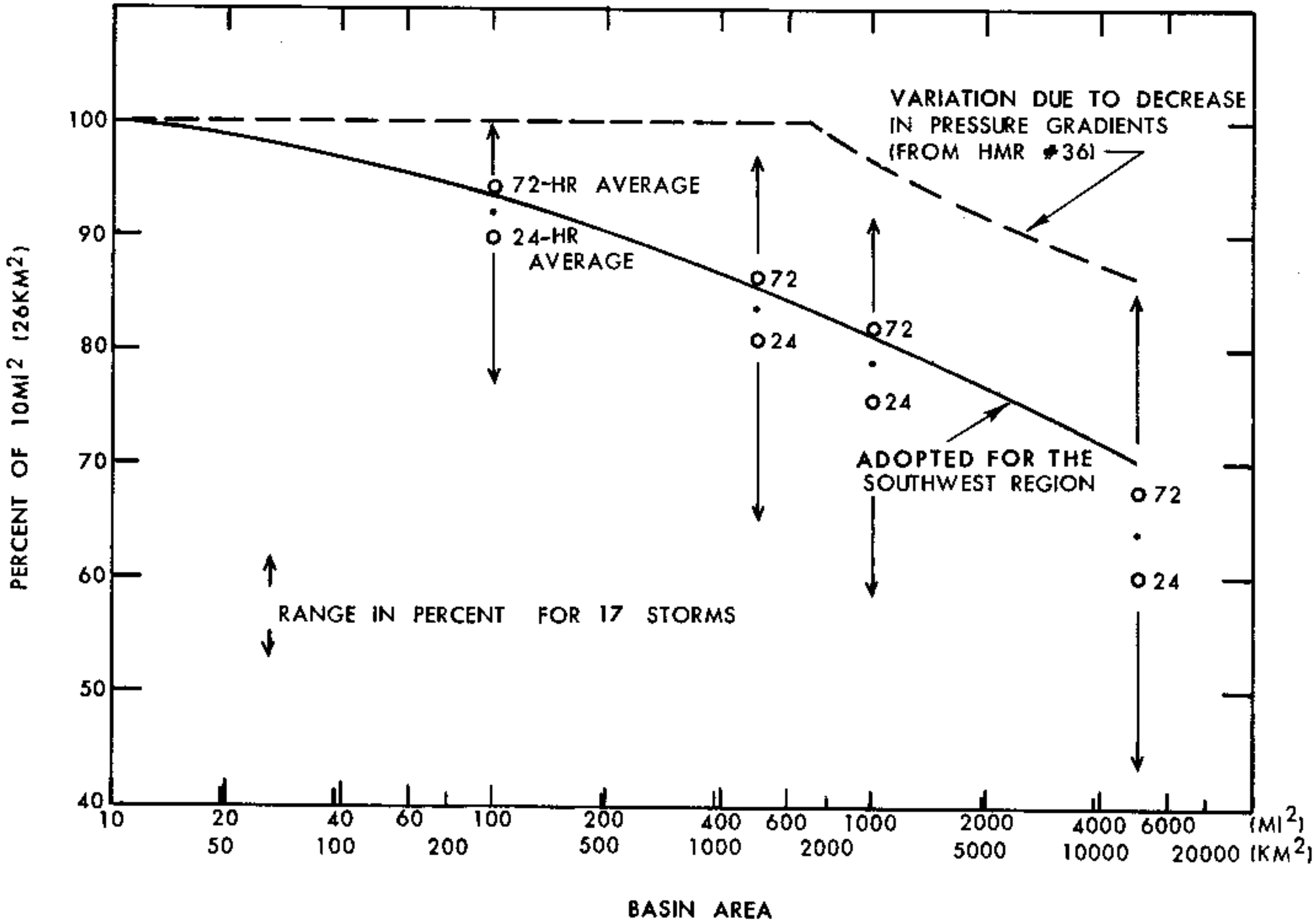

Figure 3.20.--Variation of orographic PMP with basin size.

An approximate method was used to take into account both the reduction due to lateral extent of a basin and the fact that at a given time slopes oriented in only one direction can be effective. This was to analyze the depth-area relations of most orographically-influenced rainfalls for major storms of record in the Southwestern States. The approximation is that we assume precipitation at high elevations is mostly orographic.

3.4.2 Storm Data.

The storms used in the analysis are listed in table 3.5 along with the 10-mi^2 (26-km^2) precipitation for 24 and 72 hours. The 1000-mi^2 (2590 km^2) values for 24 and 72 hours are given in percentages of the 10-mi^2 (26-km^2) values. Some storms with centers at lower elevations, such as the September 3-9, 1939 storm in California, were omitted from the storm sample. If the duration of the storm is less than 72 hours, the actual duration is asterisked in the right-hand column of table 3.5. All storms occurred within the southwest study region.

Figure 3.21 shows 1000-mi^2 (2590-km^2) 72-hr precipitation expressed in percent of the 10-mi^2 (26-km^2) value. The data do not suggest a simple relation between magnitude of rainfall at 10 mi^2 (26 km^2), and the percent at 1000 mi^2 (2590 km^2). A similar plot (not shown) for 24-hr durations

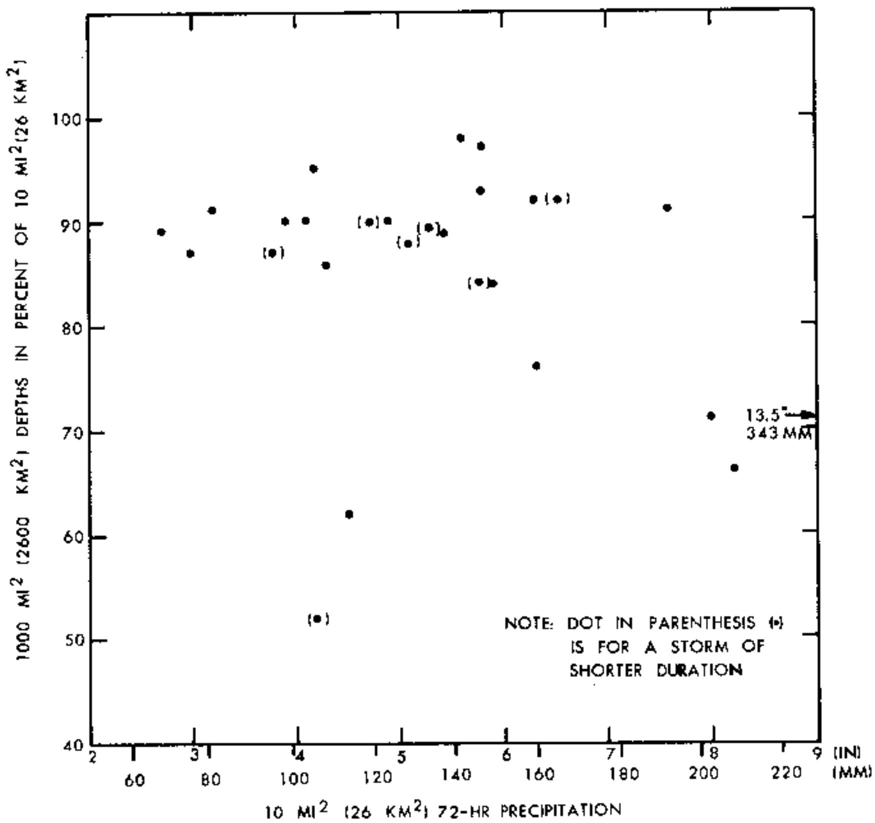

Figure 3.21.--1000-mi^2 (2590-km^2) storm depths relative to 10-mi^2 (26-km^2) depths for 72-hr rainfalls.

Table 3.5.--Data analyzed for determining depth-area variation of orographic PMP

Storm date	24-hr 10-mi^2 rainfall in.	(mm)	24-hr 1000-mi^2 rainfall in % of 10-mi^2 value	72-hr 10-mi^2 rainfall in.	(mm)	72-hr 1000-mi^2 rainfall in % of 10-mi^2 value
Arizona						
Feb. 1-7, 1905	2.3	(58)	100	5.8	(147)	97
Mar. 12-20, 1905	3.0	(76)	80	4.3	(109)	86
Apr. 9-13, 1905	3.2	(81)	78	3.9	(99)	90
Nov. 25-28, 1905	4.4	(112)	82	4.9	(124)	90
Dec. 1-4, 1906	2.7	(69)	85	5.1	(130)	88 60*
Dec. 14-17, 1908	3.9	(99)	90	6.3	(160)	92
Dec. 17-24, 1914	3.1	(79)	77	5.9	(150)	83
Jan. 14-20, 1916	2.7	(69)	82	5.8	(147)	93
Jan. 25-30, 1916	4.0	(102)	73	5.8	(147)	84 66*
Apr. 4-9, 1926	4.0	(102)	88	4.7	(119)	90 60*
Feb. 10-22, 1927	4.3	(109)	79	7.6	(193)	91
Feb. 3-8, 1937	4.9	(124)	84	5.3	(185)	89 54*
Feb. 26-Mar. 4, 1938	5.8	(147)	90	6.5	(165)	92 66*
Mar. 11-17, 1941	3.3	(84)	67	6.3	(160)	76
Aug. 26-31, 1951	6.9	(175)	71	13.5	(343)	71
Sept. 3-7, 1970	4.7	(119)	64	8.0	(203)	71
Colorado						
Dec. 14-17, 1908	3.7	(94)	89	5.6	(142)	98
Sept. 3-7, 1909	2.9	(74)	93	4.1	(104)	90
Oct. 4-6, 1911	8.1	(206)	59	8.2	(208)	66
Mar. 19-21, 1912	2.6	(66)	92	3.8	(96)	87 54*
June 26-29, 1927	2.8	(71)	89	5.4	(137)	89
Sept. 6-10, 1927	2.4	(61)	87	4.2	(107)	95
July 27-Aug. 7, 1929	2.5	(64)	84	3.0	(76)	87
Aug. 25-29, 1932	2.2	(56)	77	2.7	(69)	89
Sept. 18-23, 1941	3.0	(76)	90	3.2	(81)	91
June 1-3, 1943	2.2	(56)	91	4.2	(107)	52 42*
Utah						
May 31-June 5, 1943	3.1	(79)	65	4.5	(114)	62

Note: 10 mi^2 = 26 km^2 and 1000 mi^2 = 2590 km^2.
*Storm duration when less than 72 hours.

indicates a slight trend of lower percents for the greater 10-mi^2 (26-km^2) values; however we do not believe this trend is significant. We chose to use a depth-area relation not related to magnitude of the 10-mi^2 (26-km^2) value.

Another aspect of depth-area variation is whether one relation can be used for all months of orographic PMP. The 1000-mi^2 (2590-km^2) rainfall for 24 hours, in percent of 10-mi^2 (26-km^2) values, column 2 of table 3.5, were averaged for each month. The results did not show a clear-cut seasonal trend. Similar analysis of 72-hr values was also inconclusive. The limited number of storms and their uneven seasonal distribution are handicaps in defining seasonal trends. Without data to indicate otherwise, and to avoid unduly complicating one aspect of the PMP criteria, we recommend use of one depth-area relation for all months.

3.4.3 Adopted Variation

An average depth-area relation was developed from the 17 storms in table 3.5 with 10-mi^2 (26-km^2) 24-hr amounts $\geq$ 3.0 inches (76 mm). These averages are shown in figure 3.20 separately for the 24- and 72-hr durations along with the range in ratios from the two durations indicated by arrow points. The averages are somewhat less than the adopted areal variation used in the adjoining Northwest Region (HMR No. 43). Considering the ranges in the data, and that nonorographic precipitation in the data would tend to lower the ratios, we recommend the same areal variation as in the Northwest Region. This is the solid curve shown in figure 3.20.

3.5 Durational Variation

3.5.1 Background

Variation of orographic precipitation with duration depends on the durational variation of winds and moisture. The measure of moisture used in this study is surface dew point. During major storms there are periods when depth of the moist layer is limited by drier air aloft. In a study for the Northwest (HMR No. 43) a variation in relative humidity with duration during the 3-day PMP storm was introduced, based upon some recent storms of record. For computations of PMP with the orographic model on the Sierra slopes of California (HMR No. 36) an equivalent procedure was used for taking into account the variation of relative humidity. This was to calibrate the computed orographic precipitation by comparison with observed values. The longer the duration, the lower the calibration factor. We postulated that the lowering in relative humidity was responsible for variation of the calibration factor with duration.

In this section durational variation of winds, moisture, and relative humidity for data in the Northwest and California study areas will be compared with similar data for the Southwest. Finally, an adopted variation will be described.

3.5.2 Variation of Maximum Winds

The variation with duration of maximum 6-hr incremental winds for 500- and 900-mb (50- and 90-kPa) pressure levels is shown for Tucson, Ariz. by the solid curves in figure 3.22. These variations are the average of 10 windy periods for each level that contained the highest instantaneous winds at

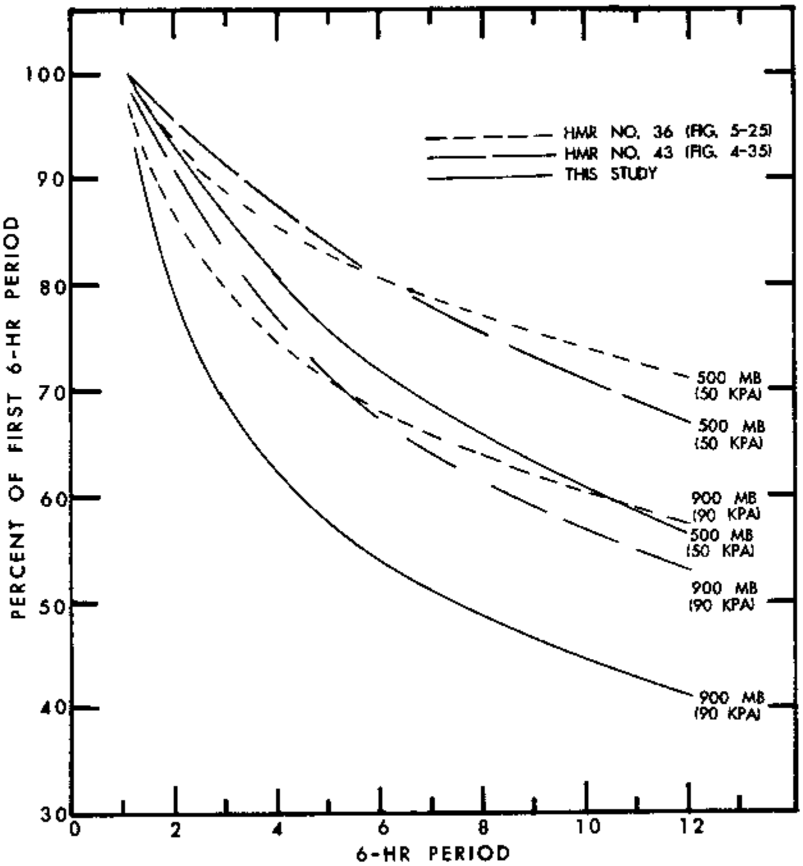

Figure 3.22.--Durational variation of maximum winds at Tucson, Arizona compared with variations for adjoining regions.

Tucson (1956-69). While the instantaneous winds were definitely greater during the winter months, the amount of variation with duration did not show a consistent correlation with time of year. For each of the windy periods, the highest average wind for consecutive observations was determined, and each durational average expressed in percent of its instantaneous highest value. From twice-a-day observations, 2 consecutive observations were considered for a 12-hr average, etc., to 7 consecutive observations for a 72-hr average. The durational decay of winds was then converted to give the durational variation of 6-hr incremental winds. The 10 cases were then averaged.

For comparison the durational variations for these same two levels for the Northwest (HMR No. 43, fig. 4-35) and California (HMR No. 36, fig. 5-25) are shown in figure 3.22 by long and short dashes, respectively. The variations for the two adjoining regions are quite similar because most of the basic data was the same. The Tucson winds have a decidedly greater decrease with duration. This is reasonable from the standpoint that the Tucson winds were restricted to the southerly component, the important direction to moisture inflow for most of the Southwest study region. Extreme westerly winds are stronger and longer lasting.

3.5.3 Variation of Maximum Moisture

Highest 12-hr persisting 1000-mb (100-kPa) dew points are used as the index to moisture assuming a pseudo-adiabatic lapse rate. For the Southwest States, 12-hr persisting 1000-mb (100-kPa) dew points for durations extending out to 3 days (U. S. Weather Bureau 1948) were considered at 7 stations well spaced over the region.

The maximum persisting dew points for 6, 12, 24, 36, 48, 60 and 72 hours for each of the 12 months at each station were expressed in inches of precipitable water assuming a saturated psuedo-adiabatic atmosphere and then in percent of the 12-hr values.

Smooth seasonal curves (not shown) of these percents for each duration were then constructed. These curves showed small random fluctuations in percents for each station not forming a discernible regional pattern. Table 3.6 lists the 7 stations and the 12-month average 3-day moisture in percent of the 12-hr moisture. One durational curve was adopted, as shown in figure 3.23. Similar curves for California and the Northwest are shown for comparison in the figure.

Table 3.6.—Durational variation of maximum moisture of the Southwest

Station	3-day moisture in percent of max. 12-hr moisture
Grand Junction, Colo.	84
Salt Lake City, Utah	82
Winnemucca, Nev.	80
Tonopah, Nev.	80
Yuma, Ariz.	84
Phoenix, Ariz.	82
Modena, Utah	79

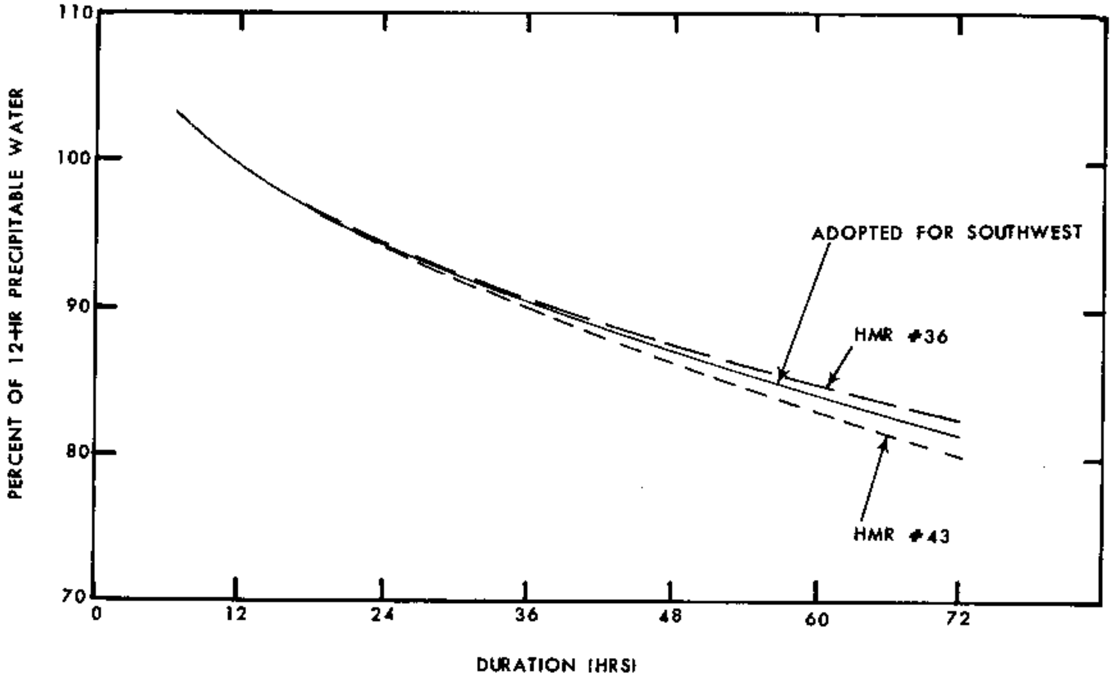

Figure 3.23.--Durational variation of precipitable water.

3.5.4 Variation of Relative Humidity

Four recent storms in Arizona (two in winter and two in summer) were selected for analysis of relative humidity (RH) from the surface to 500 mb (50 kPa). The average surface to 500-mb relative humidity for each of two soundings was plotted on a time graph for each storm. From a smooth curve joining these data, the maximum 6-, 12-, 18-, 24- ... hr relative humidity for the surface to 500 mb was determined and expressed in percent of the 6-hr value. The storms considered and the durations averaged are shown in figure 3.24. An envelopment of these percents is given by the upper solid curve in this figure. For comparison with the variation used in HMR No. 43, the durational curve was expressed in terms of 6-hr incremental RH values. This is shown by the lower solid curve. The comparable RH values from HMR No. 43 are given by the dashed curve. The variation based on four Arizona storms generally shows a greater decrease with succeeding 6-hr increments.

3.5.5 Orographic Model Computation

One method of evaluating the durational variation of precipitation is to make computations with the orographic computation model. Tests of the detailed model (which includes consideration of the slope of the inflow wind profile) show that resulting durational variations are strongly dependent on the height and length of the slope so that a different durational variation would result for each different ground profile.

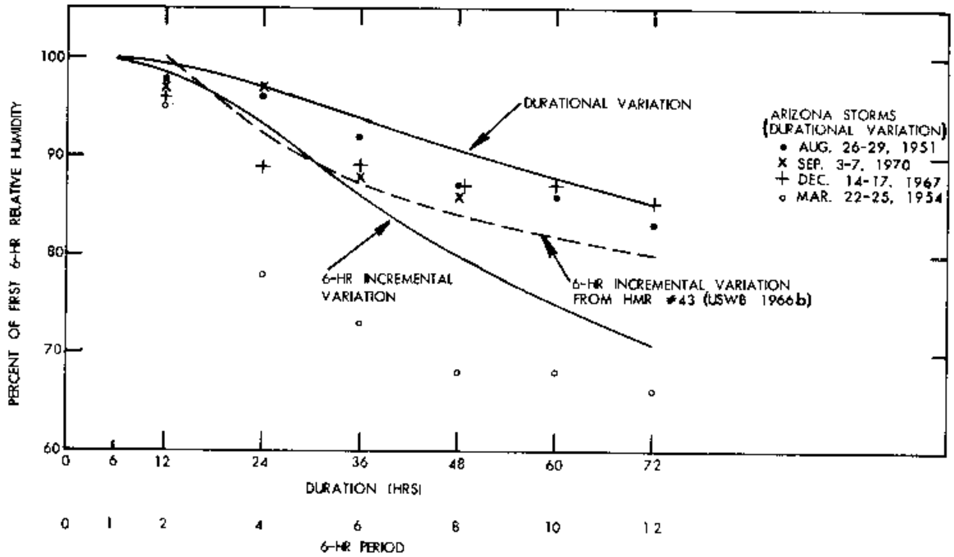

Figure 3.24.--Adopted durational variation in relative humidity and supporting data.

A simplified orographic model (World Meteorological Organization 1973) was used to evaluate differences in precipitation with duration. This is

$$R = \overline{V}_1 \left(\frac{W_1 - W_2 \dfrac{\Delta p_1}{\Delta p_2}}{Y} \right) \qquad (3.1)$$

where:

R = precipitation
$\overline{V}_1$ = mean inflow wind
W_1, W_2 = inflow and outflow precipitable water
Δp_1, Δp_2 = inflow and outflow pressure differences
Y = horizontal distance.

This model also yields somewhat different durational variations depending on the height of the terrain profile, but the differences are not as great with this simplified model since the inflow wind profile is given as one average value. We believe it is a satisfactory tool where only relative magnitudes are required.

For the computations, the winds, moisture, and relative humidity for the northern border of the region were obtained from HMR No. 43. Near the southern border we used the values of parameters in Arizona described in 3.5.2 to 3.5.4. A lift of 150 mb (15 kPa) was assumed at both locations. For the southern location the slope is from 1000 mb (100 kPa) to 850 mb (85 kPa). For the northern location it is from 850 mb (85 kPa) to 700 mb (70 kPa). The Y distance is held constant. A nodal surface of 300 mb (30 kPa) is assumed. The mean inflow wind for the southern location is an average of the 900-, 700-, and 500-mb (90-, 70- and 50-kPa) winds. For the northern location, it is an average of the 700- and 500-mb (70- and 50-kPa) winds. Table 3.7 shows details of the computations made for the 1st, 4th, 8th and 12th 6-hr periods. Rainfall computations were made for January and August in both locations. The 12th period averages 33% of the 1st for the southern border and 39% for the northern border (fig. 3.25). The southern location shows 6% more decrease in precipitation than the northern border region (relative to the first 6-hr value) for each of the 6-hr periods.

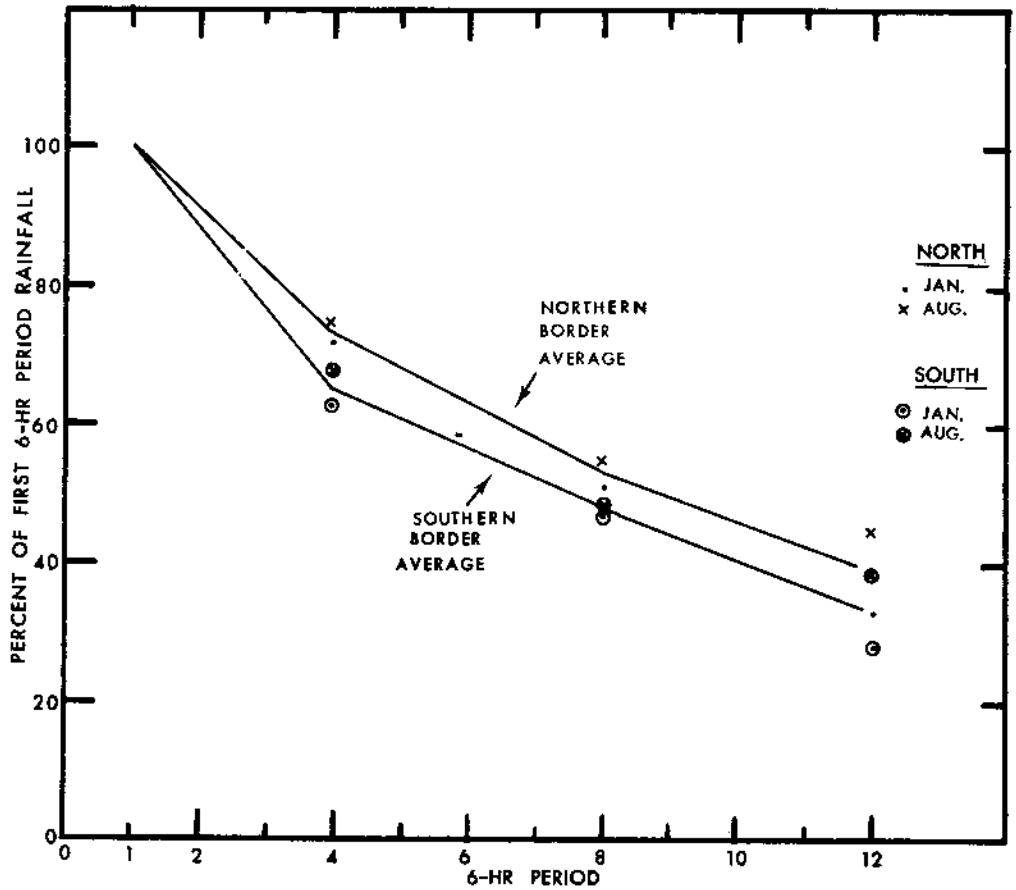

Figure 3.25.--Durational variation in orographic precipitation near northern and southern borders of Southwest region (from orographic model).

3.5.6 Guidance from Observed Precipitation

HMR No. 36 Rev. (U.S. Weather Bureau 1969) shows a tendency in more intense storms for less decrease in rain for longer durations in the north than in the south. This latitudinal variation in the durational variation of orographic PMP was based on observed precipitation along the Coastal and Sierra Mountains of California at high elevation stations during major storms.

Since orographic precipitation is dependent on the strength of moisture-bearing winds flowing against the mountains, one could expect a greater de-

Table 3.7. --Computation of durational variation of orographic precipitation for the Southwest States using a simplified orographic model (eq. 3.1)

Near northern border	Near southern border
ΔP_1 = 850-300 = 550 mb (85-30 = 55 kPa)	ΔP_1 = 1000-300 = 700 mb (100-30 = 70 kPa)
ΔP_2 = 700-300 = 400 mb (70-30 = 40 kPa)	ΔP_2 = 850-300 = 550 mb (85-30 = 55 kPa)

Precipitable water, in. (mm), considering decrease in RH

6-hour period	January W_1 in. (mm)	January W_2 in. (mm)	August W_1 in. (mm)	August W_2 in. (mm)	January W_1 in. (mm)	January W_2 in. (mm)	August W_1 in. (mm)	August W_2 in. (mm)
1	0.60 (15)	0.27 (7)	1.68 (43)	0.93 (24)	1.45 (37)	0.85 (22)	3.85 (85)	2.21 (56)
4	.47 (12)	.20 (5)	1.34 (34)	.71 (18)	1.19 (30)	.67 (17)	2.76 (70)	1.76 (45)
8	.39 (10)	.16 (4)	1.13 (29)	.58 (15)	.97 (25)	.53 (14)	2.27 (58)	1.42 (36)
12	.32 (8)	.16 (4)	.95 (24)	.47 (12)	.80 (20)	.42 (11)	1.87 (48)	1.13 (29)

Average wind (percent of first 6-hour period) for the pressure levels to 500 mb (50 kPa)

6-hour period	Near northern border	Near southern border
1	100	100
4	84	72
8	68	58
12	60	50

R (from substitution in equation 3.1) in percent of 1st 6-hr period value

6-hour period	January	August	January	August
1	100	100	100	100
4	72	75	63	68
8	51	55	47	50
12	33	45	28	39

crease with duration in Arizona than in California because maximum winds for California (HMR No. 36) decay less with duration than those in Arizona. A study was made of the durational variation of precipitation for high elevation stations in Arizona during major storms. The storms and stations used are shown in table 3.8, along with 48/24- and 72/24-hr durational ratios. The table also gives similar ratios for high elevation stations during major storms in southern California. All the ratios are based on scaling the largest 24-, 48-, and 72-hr consecutive rains from mass rainfall curves. For the earlier winter Arizona storms, only one station's rainfall was considered, that with the greatest rainfall.

The 72/24-hr ratios for the data of table 3.8 are compared on figure 3.26. The points labeled "A" are from southern California; those labeled "B" are from Arizona. Averages of the 72/24-hr rain ratios are 1.78 for southern California and 1.45 for Arizona. The southern California data are part of the information used to revise HMR No. 36 (U. S. Weather Bureau 1969).

A question may be raised about seasonal variation in the depth-duration relation. The Arizona storms show both high and low 72/24-hr rain ratios for the same months; in February the ratios for four storms range from 2.13 to 1.08. The August 1951 storm 72/24-hr ratios averaged 1.66, the September 1970 storm, 1.38. There are not enough storms to establish a seasonal trend.

3.5.7 Adopted Variation

We have discussed several aspects of the durational variation of orographic precipitation. Some conclusions for variations in the Southwest are:

a. Comparisons of durational variations of high wind cases indicate more decrease with increasing duration than in the Northwest.

b. The variation of moisture with duration is about the same as in California and the Northwest.

c. Relative humidity in upper air soundings during four major Arizona storms shows more decrease with duration than in the Northwest.

d. No definitive seasonal variation in the durational variations of wind, moisture or relative humidity could be found.

e. Computations with the simplified orographic model using the adopted durational variations of wind and moisture show more decrease with duration for southern Arizona compared to northern Nevada.

f. Observed major rains decidedly show more decrease with duration than rains on western slopes in southern California.

Based on this guidance, recommended durational variation near the southern boundary of the Southwest (latitude 31°) is shown in figure 3.27 with other comparisons. We recommend phasing into the relation adopted for the Northwest (HMR No. 43) at the northern boundary to the study region. Table 3.9 shows the durational variations expressed in percent of the 24-hr values.

Table 3.8.--Durational variation in major storms in orographic locations; southern California and Arizona

Storm date Arizona	Elevation ft	m	Station	Rain ratios $\frac{48}{24}$ hr	$\frac{72}{24}$ hr	Average ratio $\frac{48}{24}$ hr	$\frac{72}{24}$ hr
Sept. 3-6, 1970	6900	2103	Flagstaff	1.28	1.28		
	7405	2257	Beaver Creek	1.15	1.15		
	6000	1829	Crown King	1.15	1.15		
	6300	1920	Gordon Cnyn.	1.43	1.43		
	7650	2332	Woods Cnyn.	1.10	1.10		
	6970	2124	Workman Creek	1.09	1.09		
	6700	2042	Cagle Cabin	1.07	1.07		
	8180	2493	Hawley L.	1.51	1.51		
	6875	2096	Kitt Peak	1.27	2.18		
	7945	2422	Palisade R.S.	1.48	1.87		
						1.25	1.38
Aug. 26-31, 1951	5708	1740	Camp Wood	1.59	1.82		
	5500	1676	Upper Prkr.Cr.	1.35	1.67		
	6970	2124	Workman Creek	1.34	1.65		
	8400	2560	Bright Angel R.S.	1.28	1.28		
	6000	1829	Crown King	1.93	2.11		
	6000	1829	Tonto Creek	1.31	1.58		
	5100	1554	Sierra Ancha	1.16	1.31		
	4500	1372	Pinal Ranch	1.25	1.35		
	5000	1524	Payson	1.69	2.03		
	4607	1404	Natural Bridge	1.47	1.86		
						1.44	1.66
Dec. 14-17, 1908	4607	1404	Natural Bridge	1.36	1.62		
Nov. 25-28, 1905	4500	1372	Pinal Ranch	1.11	1.11		
Feb. 11-17, 1927	4607	1404	Natural Bridge	1.51	1.77		
Dec. 17-24, 1914	4800	1463	Rosemont	1.21	1.33		
Feb. 1-7, 1905	4700	1433	Yarnell	1.61	2.13		
Mar. 12-20, 1905	5345	1629	Prescott	1.43	1.43		
April 3-11, 1926	6000	1829	Crown King	1.03	1.25		
Feb. 5-8, 1937	5345	1629	Prescott	1.08	1.08		
Feb. 27-Mar.4, 1938	6903	2104	Flagstaff	1.03	1.17		
Arizona storm averages						1.28	1.45

Table 3.8.--Durational variation in major storms in orographic locations; southern California and Arizona - Continued

Storm date Southern California	Elevation ft	m	Station	Rain ratios $\frac{48}{24}$ hr	$\frac{72}{24}$ hr	Average ratio $\frac{48}{24}$ hr	$\frac{72}{24}$ hr
Jan. 20-23, 1943	4254	1297	Opids Camp	1.42	1.48		
	5709	1740	Mt. Wilson	1.41	1.42		
	2290	698	Big Tujunga Dam	1.33	1.35		
	2650	808	Hoegee's Camp	1.41	1.44		
	5239	1594	Squirrel Inn	1.27	1.36		
	4320	1317	Camp Baldy	1.38	1.43		
	5740	1750	Crystal Lake	1.41	1.46		
	6800	2073	Big Bear Dam	1.50	1.58	1.39	1.44
Feb. 27-Mar 3, 1938	4254	1297	Opids Camp	1.18	1.49		
	5850	1783	Mt. Wilson	1.22	1.71		
	2050	625	Big Tujunga Dam	1.25	1.59		
	2650	808	Hoegee's Camp	1.21	1.76		
	5239	1594	Squirrel Inn	1.12	1.47		
	4320	1317	Camp Baldy	1.26	1.55		
	5740	1750	Crystal Lake	1.17	1.59		
	6800	2073	Big Bear Dam	1.18	1.34	1.20	1.56
Feb. 10-22, 1927	4254	1297	Opids Camp	1.41	2.00		
	5850	1783	Mt. Wilson	1.34	2.11		
	2650	808	Hoegee's Camp	1.39	1.91		
	5239	1594	Squirrel Inn	1.43	2.09		
	4300	1310	Camp Baldy	1.43	1.97		
	6800	2073	Big Bear Dam	1.46	1.96	1.41	2.01
April 3-11, 1926	4254	1297	Opids Camp	1.24	1.63		
	5850	1783	Mt. Wilson	1.28	1.55		
	2650	808	Hoegee's Camp	1.28	1.81		
	5239	1594	Squirrel Inn	1.50	1.87		
	4300	1310	Camp Baldy	1.38	1.62		
	6800	2073	Big Bear Dam	1.42	1.54	1.35	1.66
Dec. 18-28, 1921	5850	1783	Mt. Wilson	1.40	1.66		
	5239	1594	Squirrel Inn	1.79	2.27		
	4300	1310	Camp Baldy	1.56	1.90	1.58	1.94
Jan. 13-16, 1916	5850	1783	Mt. Wilson	1.43	1.55		
	5239	1594	Squirrel Inn	1.29	1.46		
	4300	1310	Camp Baldy	1.44	1.48	1.39	1.50
Feb. 17-22, 1914	5850	1783	Mt. Wilson	1.89	2.47		
	5239	1594	Squirrel Inn	1.63	2.39		
	6800	2073	Big Bear Dam	1.41	2.29	1.64	2.38
California Storm Averages						1.38	1.78

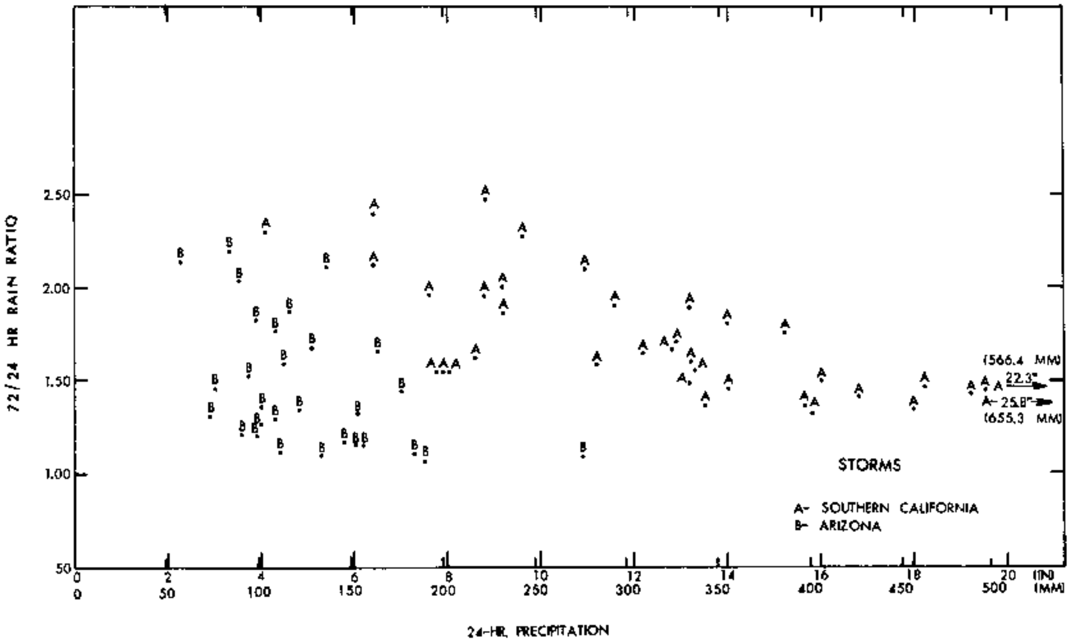

Figure 3.26.--Ratios of 72/24-hr rains at high elevations from major storms in southern California and Arizona.

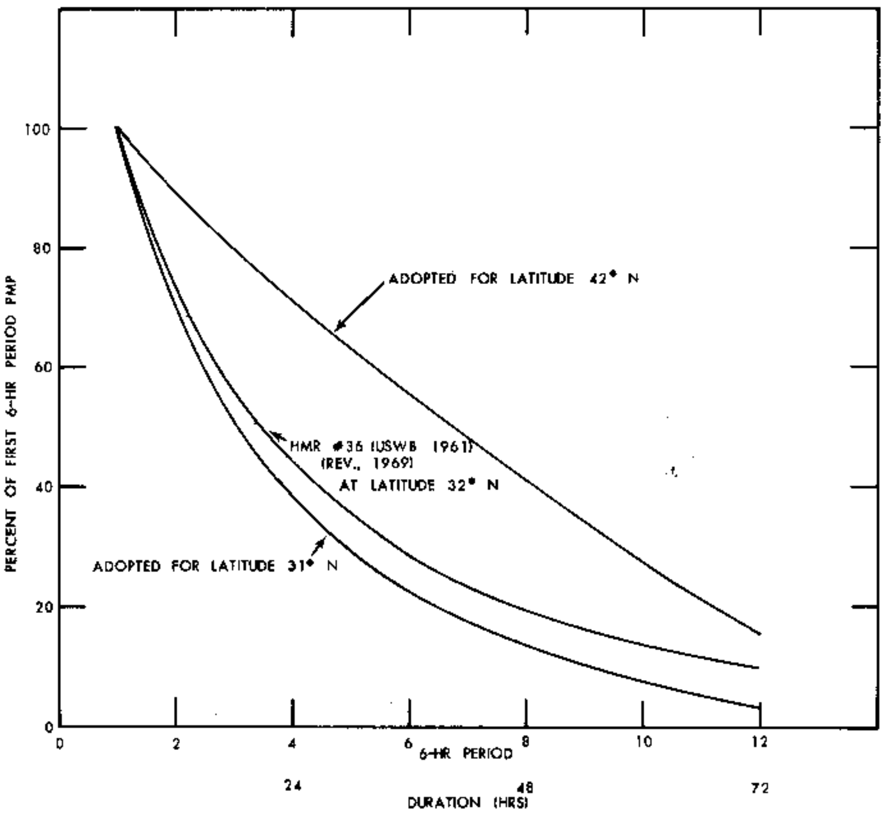

Figure 3.27.--Adopted durational variation in orographic PMP. (Percent of first 6-hr period value at latitudes near the northern and southern borders of the Southwest States.

Table 3.9.--Durational variation of orographic PMP

Latitude °N	Percent of 24-hr value					
	6 hr	12	18	24	48	72
42	28	55	79	100	161	190
41	29	56	79	100	160	189
40	30	57	80	100	159	187
39	30	57	80	100	157	185
38	31	58	81	100	155	182
37	32	59	81	100	152	177
36	33	60	82	100	149	172
35	34	61	82	100	146	167
34	35	62	83	100	143	162
33	36	63	84	100	139	157
32	37	64	84	100	135	152
31	39	66	85	100	132	146

4. LOCAL-STORM PMP FOR THE SOUTHWESTERN REGION AND CALIFORNIA

4.1 Introduction

This chapter provides generalized estimates of local or thunderstorm probable maximum precipitation. By "generalized" is meant that mapped values are given from which estimates of PMP may be determined for any selected drainage.

4.1.1 Region of Interest

Local-storm PMP was not included in the "Interim Report, Probable Maximum Precipitation in California" (HMR No. 36). During the formulation of the present study, we decided that the local-storm part of the study should include California west of the Sierra Nevada. It was also noted that PMP for summer thunderstorms was not considered west of the Cascade Divide in the Northwestern Region (HMR No. 43). As stated in the latter report, "No summer thunderstorms have been reported there (west of the Divide) of an intensity of those to the east, for which the moisture source is often the Gulf of Mexico or Gulf of California. The Cascade Divide offers an additional barrier to such moisture inflows to coastal areas where, in addition, the Pacific Ocean to the west has a stabilizing influence on the air to hinder the occurrence of intense summer local storms." Therefore, it was necessary to establish some continuation of the Cascade Divide into California so that the local-storm PMP definition would have continuity between the two regions.

The stabilizing influence of the Pacific air is at times interrupted by the warm moist tropical air from the south pushing into California, although it is difficult to determine where the limit of southerly flow occurs. General storms having the tropical characteristic of excessive thunderstorm rains are observed as far north as the northern end of the Sacramento Valley. Thus, a northern boundary has been selected for this study, excluding that portion of

California north and west of a line extending from the Cascade Divide at the California-Oregon border, southwestward along the coastal mountain ridge-line to a point near 41°N, 123°W, and then directly to Cape Mendocino on the California coast, (see fig. 4.1).

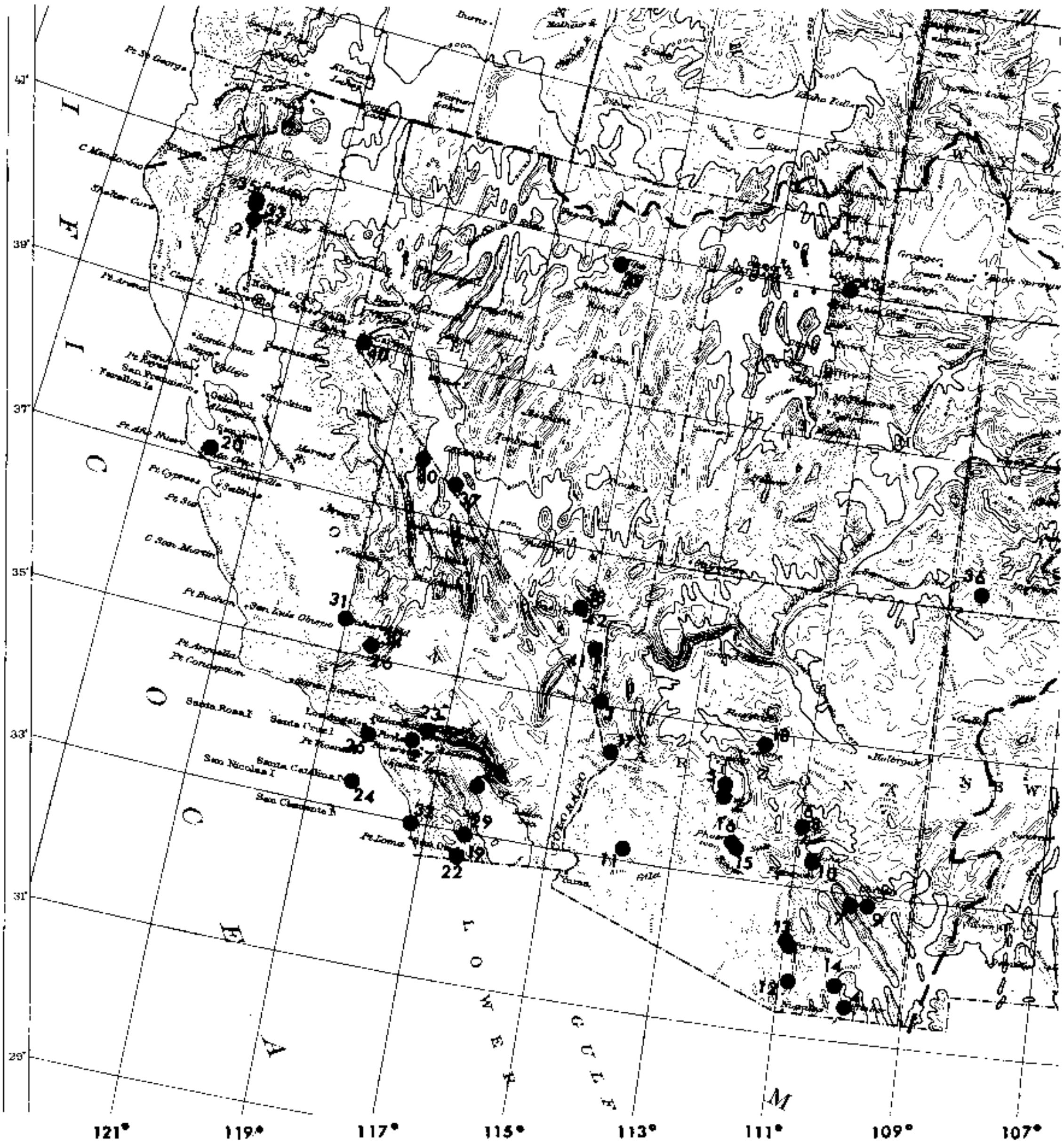

Figure 4.1.--Location of short-duration extreme rainfalls. (See table 4.1 for storm identification).

4.1.2 Definition of Local Storm

One of the most important processes in extreme local storms is the strong convective lifting of moist air. Most storms are thunderstorms, but because thunder is not necessarily heard during extreme rainfall, the term local storm is used.

Record storms used as the basis for local-storm PMP are defined as unusually heavy rains exceeding 3.0 inches (75 mm) in 3 hours or less that are reasonably isolated from surrounding rains. This definition was chosen to provide a basis for selection of candidate storms (generally point rainfall amounts), and because many of the most extreme storms are independent of widespread rain patterns. Thunderstorms with point rainfalls less than the most intense of record have of course been observed in general-storm situations.

The records for California west of the Sierra Nevada contained only a few storms meeeting the criteria set for local storms. Thunderstorm frequency within the Central Valley is one of the lowest in the region studied. Because of the absence of prototype local storms as defined above a decision was made, for California west of the Sierra Nevada, to include extreme point rainfalls that were imbedded in general-type precipitation patterns and that occurred during the warm season.

Our sample of extreme local storms (thunderstorms) in the Southwestern Region have short lifetimes as compared to the supercells observed over the Great Plains. Their lifetime is usually 1 to 2 hours, occasionally as long as 3 hours. Some isohyetal patterns are the combined result of rains within a 6-hr period from two or more storms. Thus 6 hours has been used as the duration limit for local PMP estimates.

PMP values derived in this chapter are estimates of the upper limit of rainfall resulting from summer or early fall local storms. Such storms, while producing the most intense point rainfalls of record, characteristically show a rapid decrease in rainfall with increasing area. We have extended the criteria out to 500 mi^2 (1,295 km^2).

4.2 Storm Record

Determination of PMP for a region is based in part on the most extreme precipitation of record. A survey was made of extreme rains within the study region meeting the definition of local storms in section 4.1.2. The most intense short-period rains found are listed chronologically by State in table 4.1, except for the four long-duration storms in California.

Records, although not complete, permit us to examine a period of about 90 years. Within this span, the number of observers has increased and the manner and detail in recording unusual events has improved, so the storm record is strongly biased toward more recent events. Furthermore, the storms listed in table 4.1 represent only those known to the NWS Hydrometeorological

Table 4.1.--Major short-period rains of record in the Southwestern States and all of California

	Location		Lat., N ° '	Long., W ° '	Elevation ft	Elevation m	Date	Duration min	Amount in.	Amount mm	Reference†	Remarks
Arizona												
1.	Tucson	(n.d.)	32 13	110 58	2360	720	7/11/78*	105	5.10	130	MWR, 7/1878	
2.	Farley's Camp	(n.d.)	34 02	112 18	2700	825	8/28/91*	90	3.10	79	MWR, 8/1891	
3.	Ft. Mohave		35 03	114 36	540	165	8/28/98*	45	~8	203	CCSB, 8/1898	Amount questionable.
4.	Bisbee	(n.d.)	31 27	109 55	5440	1650	7/22/10	70	4.25	108	Green and Sellers,1964	
5.	Crown King	(n.d.)	34 12	112 20	6000	1830	8/11/27	170	4.90	124	Leopold, 1943	
6.	Sierra Ancha	(n.d.)	33 48	110 58	5100	1550	9/10/33	105	4.28	109	1	At experimental forest site.
7.	Pima	(n.d.)	32 51	110 02	4000	1220	8/02/39	60	3.10	79	Langbein, 1941	
8.	Sierra Ancha	(n.d.)	33 48	110 58	5100	1550	8/05/39	140	5.02	128	USCE, 1961	
9.	Thatcher	(n.d.)	32 51	109 46	2800	855	9/16/39	90	4.1	104	USCE, 1961	
10.	Globe		33 20	110 43	3540	1080	7/29/54	40	3.5	89	2	
11.	Welton (25NE)	(n.d.)	33 10	113 45	2800	855	8/23/55	180	~6	~150	3	
12.	Santa Rita		31 45	110 51	4400	1340	6/29/59	60	4.5	114	4	
13.	N. Tucson	(n.d.)	32 18	111 00	2450	750	9/06/64	~120	~5	~125	5	
14.	Walnut Gulch		31 42	110 05	4600	1400	9/10/67	45	3.35	85	Osborn and Renard,1969	
15.	Tempe	(n.d.)	33 23	111 58	1180	360	9/14 69	60	3.52	89	6	
16.	Phoenix		33 27	112 04	1100	355	6/22/72	120	5.25	133	USCE, 1972	
17.	Lk. Havasu City	(n.d.)	34 26	114 20	~500	~150	7/19/74	~60	~4.5	~115	7	
18.	Sedona	(n.d.)	34 53	111 46	~4800	~1460	7/14/75	~60	3.5	89	Selvidge, 1975	
California												
19.	Campo		32 36	116 28	2590	760	8/12/91*	80	11.5	292	USWB, 1960	Amount is a minimum.
20.	Wrights		37 08	121 55	1600	490	9/12/18	~60	~3.5	~90	Weaver, 1962	Tropical cyclone influence.
21.	Red Bluff		40 09	122 15	340	104	9/14/18	180	4.70	119	Weaver, 1962	Tropical cyclone influence.
22.	Campo		32 36	116 28	2590	760	7/18/22	120	7.1	180	CD, 7/1922	
23.	Squirrel Inn		34 14	117 15	5280	1610	7/18/22	90	5.01	127	CD, 7/1922	
24.	Avalon		33 21	118 19	10	3	10/21/41	210	5.53	140	Weaver, 1962	Imbedded in general storm.
25.	Los Angeles		34 00	118 10	500	152	3/03/43	180	3.32	84	Weaver, 1962	Imbedded in general storm.
26.	Tehachapi		35 08	118 27	3975	1210	10/06/45	~120	3.17	81	8	
27.	Cucamonga	(n.d.)	34 05	117 25	1650	500	9/29/46	80	3.2	81	9	
28.	La Quinta	(n.d.)	33 40	116 19	50	15	7/22/48	~210	~3	~75	USCE, 1957	
29.	Vallecito		32 58	116 21	1450	440	7/18/55	70	7.1	180	10	
30.	Chiatovich Flat		37 44	118 15	10320	3140	7/19/55	150	8.25	210	Kesseli and Beaty, 1959	Location uncertain.
31.	Bakersfield		35 25	119 03	475	145	6/07/72	75	3.5	89	Bryant, 1972	Tropical cyclone influence.
32.	Encinitas	(n.d.)	32 59	117 15	100	30	10/12/89*	8 hr	7.58	192	MWR, 10/1889	Possible tropical cyclone.
33.	Kennett		40 23	122 12	730	222	5/09/15	8 hr	8.25	210	Weaver, 1962	Imbedded in general storm.
34.	Tehachapi		35 08	118 27	3975	1210	9/30/32	5 hr	~6.2	~155	CD, 10/1932	Tropical cyclone influence.
35.	Newton		40 22	122 12	700	212	9/18/59	5 hr	~10.6	~270	Weaver, 1962	Imbedded in general storm.
Colorado (west of Continental Divide)												
36.	Mesa Verde N.P.	(n.d.)	37 12	108 29	7070	2160	8/03/24	45	3.50	89	CD, 8/1924	Duration from Bureau of Reclamation, Denver.

† See footnotes at end of table, p. 107

Table 4.1.--Major short-period rains of record in the Southwestern States and all of California--Continued

Location		Lat., N ° '	Long., W ° '	Elevation ft	m	Date	Duration min	Amount in.	mm	Reference†	Remarks
Nevada											
37. Palmetto		37 27	117 42	6700	2040	8/11/90*	60	8.8	224	USWB, 1960	Amount questionable.
38. Las Vegas		36 11	115 11	2175	660	6/13/55	~120	3.4	86	11	
39. Elko		40 50	115 40	5075	1660	8/27/70	60	3.64	92	CD, 8/1970	
40. Genoa	(n.d.)	38 59	119 50	4700	1450	8/07/71	58	3.50	89	12	Most of rain fell in 15 min.
41. Nelson	(n.d.)	35 43	114 49	3500	1050	9/14/74	45	3.25	83	Glancy and Harmsen, 1975	
42. Las Vegas		36 11	115 11	2175	660	7/03/75	~210	~3	~75	Randerson, 1975	
New Mexico (west of Continental Divide)											
No reports of amounts exceeding 3 in. (75 mm) in 3 hr or less.											
Utah											
43. Morgan		41 03	111 38	5150	1570	8/16/58	60	~6.75#	~170	Peck, 1958	

† Reference identification:

MWR: Monthly Weather Review, U.S. Weather Bureau, Washington, D.C.
CCSB: Climate and Crop Service Bulletin, Dept. of Agriculture (early series published monthly for each state).
CD: Climatological Data, U.S. Weather Bureau, Washington, D.C. (published monthly for each state).
USCE: U.S. Army, Corps of Engineers, Washington, D.C.
USWB: U.S. Weather Bureau, Washington, D.C.
USGS: U.S. Geological Survey, Washington, D.C.

Unpublished material; copies available from Hydrometeorological Branch, National Weather Service.

1. Letter from USCE, Los Angeles District (LAD), April 27, 1964.
2. Report from USCE, LAD, August 24, 1954.
3. Report from USCE, LAD, September 15, 1955.
4. Letter from U.S. Dept. of Agriculture, Exp. Rg. Sta., August 21, 1959.
5. Communication from USGS, Tucson, Arizona (undated).
6. Letter from Flood Control District of Maricopa Co., Arizona, October 8, 1969.
7. Communication from USCE, LAD (undated).
8. Joint Review of Flood Damage, Exerpts Kern and Inyo Counties, California, January 17, 1946.
9. Report from San Bernardino Co. Flood Control District, California, October 4, 1946.
10. Report from USCE, LAD, August 5, 1955.
11. Report from USCE, LAD, July 6, 1955.
12. Communication from USGS, Carson City, Nevada (undated).

(n.d.)- no detailed storm study made.
* - storm date prior to 1900.
\# - reported 7 in. questionable.

Branch. Information may exist about other local-storm rains that meet our criteria but are unknown to us. It is doubtful, however, that there are any observed storms that exceed the most extreme of those listed in table 4.1. The file of record storm rainfall is only as complete as is possible from the observational network, through which many extreme local storms can pass unrecorded.

Table 4.1 lists the location, date, duration, amount, and source[1] of each major local storm. Figure 4.1 shows the storm locations. The distribution of storms by State shows greatest frequency closest to warm moisture sources. Storms at Avalon and La Quinta, California and Las Vegas, Nevada exceed the 3-hr duration limit by about one-half hour, but were included because they appeared to be exceptional cases at their respective locations. The 1941 Avalon storm, and the Los Angeles storm of 1943 appear to be general-storms, but their maximum point amounts were the result of imbedded thunderstorms and were notably larger than the surrounding general-storm rains. In addition, four extreme storm values that came from durations much longer than 3 hours are listed in table 4.1 for California (Encinitas, Kennett, Tehachapi, and Newton). The meteorological description of these four storms has been presented elsewhere (Weaver 1962). They all were from either early or late cool-season general storms, or from rains produced by tropical storm moisture, but whose maximum value was very localized. Tropical storms usually affect only the southern half of California while the general frontal-type events occur mostly in the northern half of the State. On a few occasions tropical moisture penetrates northward nearly to the Oregon border. Since few cases of large rainfall from isolated storms were found in coastal California, it was believed important to this study to consider these few exceptions.

Meteorological analyses of the synoptic weather surrounding most of the other significant events listed in table 4.1 are included in a companion report to this study (Schwarz and Hansen 1978). Characteristics of moisture, instability, and inflow believed pertinent to the development of the local storm and the effects of movement and terrain on maximizing rainfall are also discussed in that volume.

4.3 Development of 1-Hr PMP

4.3.1 Introduction

The development of local-storm PMP has several steps: First, 1-hr PMP is estimated over the region for 1 mi^2 (2.6 km^2). Then, durational and areal variations are determined. The method for developing the 1-hr PMP is comparable in many respects to basic PMP approaches used in studies for other parts of the country.

Some studies, particularly those in the region east of the 105th meridian, make widespread use of the transposition of extremes within meteorologically homogeneous regions to supplement sparse data. In the Southwest, however,

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[1]Published references are listed at the end of this report, unpublished material is numerically referenced at the end of table 4.1.

terrain limits explicit transposition of observed local-storm maxima. The final 1-hr PMP map however is drawn in part by smoothing between data points thus implicitly introducing transposition.

4.3.2 Data adjustments

In studies of PMP it is assumed that observed data come from storms in which the contributing factors were not all at their maximum. Where there is sufficient storm data, a procedure for adjustment to maximum moisture, storm transposition, and smooth envelopment durationally, areally, and over a region is considered adequate for an estimate of PMP. This is the method of this study.

The following adjustments were made on the data:

a. Adjustment for maximum moisture. As in the case of convergence PMP for general storms discussed in chapter 2, moisture maximization was used to adjust short-term storms to potential moisture considered possible for the location and date. The procedure for maximization is similar to that stated in section 2.2.1; however, maximum 12-hr persisting 1000-mb (100-kPa) dew points for local storms were used (Schwarz and Hansen 1978).

b. Adjustment for elevation. The elevations of observed maximum local-storm rains in table 4.1 vary from sea level to over 10,000 feet (3,048 m). No discernable relation appears between rainfall amount and elevation for these data.

Guidance on adjustment for elevation was sought from maximum 6-consecutive clock-hour rainfall for the months of May through September at recorder stations. Plots of these data vs. station elevation for three states are presented in figure 4.2. The dashed lines envelop the body of data, and show a tendency for rainfall to decrease for stations above 4,000 to 5,000 feet (1,219 - 1,524 m).

In chapter 2, the elevation adjustment allowed for reduced moisture with increased elevation above sea level. For general-type storms, the need for sustained inflows and the effects of barriers warrented such an adjustment. In our study of local storms, however, conditions of local moisture and the evidence in figure 4.2 suggest that maximum precipitation could occur through some range of elevations. Theoretically, such a condition could result from a combination of factors, such as vertical mixing, vertical velocities, convergence effects, etc. Above some level, there must be a reduction in precipitation potential with height. At what height this reduction begins is not evident from meteorological knowledge.

We have chosen 5,000 feet (1,524 m) as the elevation of the limit to maximum effective precipitation in this study. A limit of 5,000 feet is somewhat in agreement with the results shown in figure 4.2, and is compatible with the limit established in HMR No. 43. No adjustment in precipitation is made for elevations up to 5,000 feet (1,524 m). Above this level, a decrease of 5

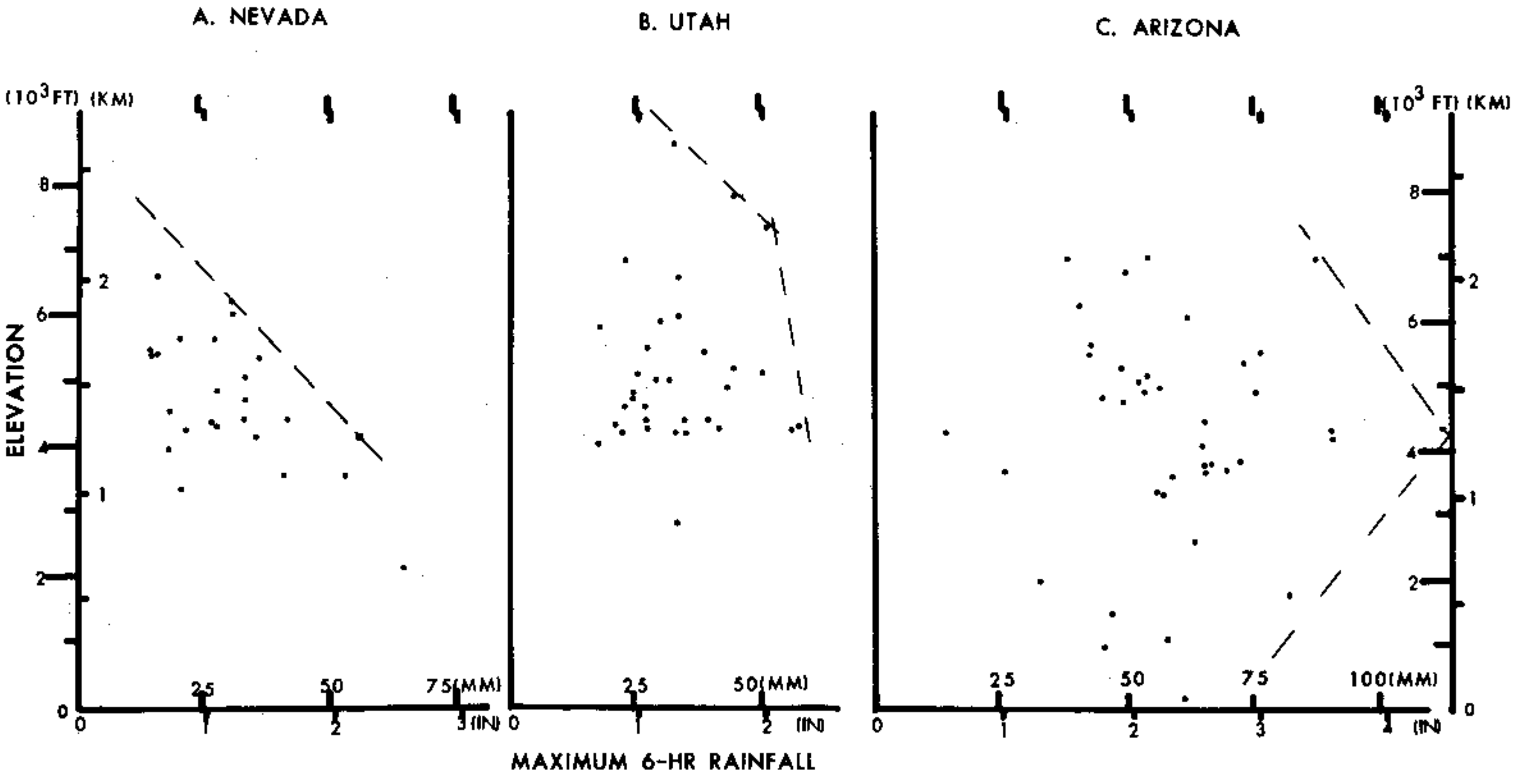

Figure 4.2.--Variation of maximum 6-hr summer recorder rainfall with elevation (period of record is 1940-1972).

percent per 1,000 feet (305 m) of additional elevation is applied. This adjustment was used to normalize all observations in table 4.1 for elevation. Similarly, this adjustment must be applied to PMP for elevations above 5,000 feet (see chapter 6).

c. Adjustment for duration. The storms in table 4.1 had durations ranging between 15 and 210 minutes (except for the four relatively longer duration storms in California). All the durations in this table were adjusted to a common duration of 1 hour. Normalization for duration has been accomplished through use of the depth-duration relations shown in figure 4.3. These relations were developed from local-storm rainfalls for May through September in the study region (see discussion, section 4.4).

4.3.2.1 Application of Adjustments to Data. Of the 43 storms listed in table 4.1, the 16 most intense and widely distributed over the region were selected. Table 4.2 shows the results of moisture maximizing and normalizing (for elevation and duration) the 16 storm amounts. Note in column 3 of table 4.2 that the effect of the elevation adjustment for those observations above 5,000 feet (1,524 m) is to increase the rain amount by 5% per 1,000 feet (305 m) above that elevation.

The maximized, normalized values given in column 7 of table 4.2 were plotted on a map at their respective locations as the lower bounds to PMP for those locations. Data were insufficient to define a regional pattern.

4.3.3 Analysis

Maximum 1-hr amounts from recorder stations (1940-72) were examined for guidance to a regional pattern of 1-hr PMP. Not all stations had complete 33-yr records. The largest 1-hr amounts at each station for the months May to September were plotted and an analysis made at 1-in. (25 mm) isohyetal interval (fig. 4.4).

All amounts exceeding 1.5 inches (38 mm) have been underlined as an aid to locating zones of maxima. Noticeable are the number of underlined amounts extending SE-NW across Arizona. These observations reflect the interaction between the terrain and moist southerly flows from the Gulf of California. A much smaller zone of maxima occurs in southern California. Large zones of minimum amounts occur over portions of the Great Basin, the Central Valley of California, and along the Pacific coast.

Further guidance was obtained from the shape of the maximum moisture pattern for August (see fig. 2.3). Lowest moisture occurs along the Pacific coast with a push of maximum values northward through east central Arizona. There is a tendency for lower values in northern New Mexico and western Colorado.

The analysis in figure 4.4 has been influenced by knowledge of the terrain. This includes allowing for stimulation of convective activity which leads to triggering of rainfall in upslope areas.

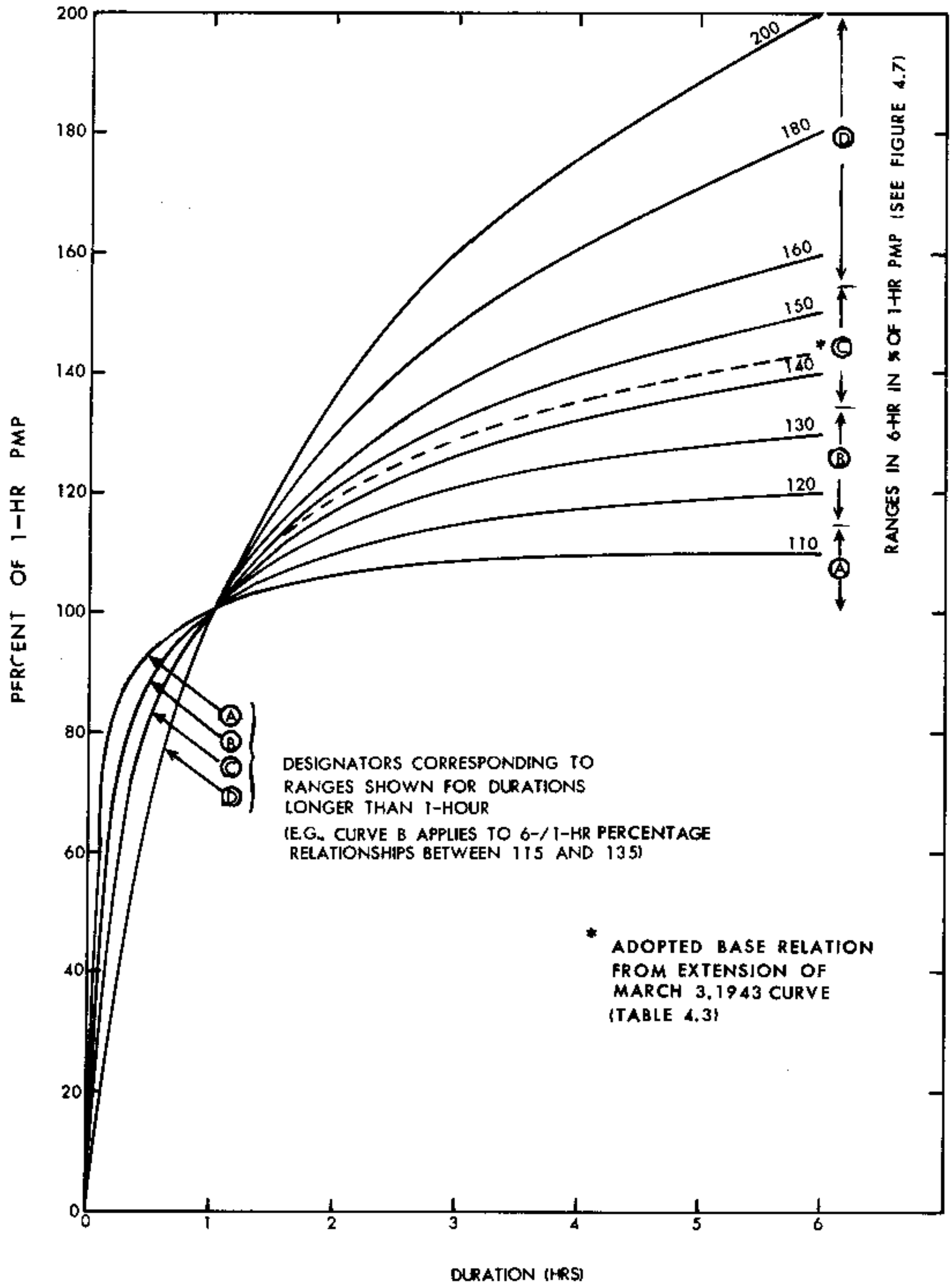

Figure 4.3.--Variable depth-duration curves for 6-hr PMP in the Southwest States and all of California.

Table 4.2.--Adjustment to most critical local-storm rainfalls

	Column:	1		2		3		4		5		6	7	
		Observed amount		Col. 1 normalized to 1-hr amount		Col. 2 adjusted to 5000 ft (1524 m)#		Storm dewpoint		Maximum dewpoint		Moisture adjustment factor	Col. 3 multiplied by Col. 6	
Storm location	Date	in.	(mm)	in.	(mm)	in.	(mm)	°F	(°C)	°F	(°C)		in.	(mm)
Palmetto, Nev.	8/11/90*	8.8**	(224)	8.8	(224)	9.5	(241)	70	(21)	74	(23)	1.22	11.6	(294)
Campo, Calif.	8/12/91*	11.5	(292)	10.4	(264)	10.4	(264)	72	(22)	75	(24)	1.16	12.1	(307)
Ft. Mohave, Ariz.	8/28/98*	8	(203)	8.4	(213)	8.4	(213)	72	(22)	77	(25)	1.28	11.8	(274)
Mesa Verde N.P., Colo.	8/03/24	3.50	(89)	3.71	(94)	4.08	(103)	65	(18)+	77	(25)	1.80	7.4	(188)
Globe, Ariz.	7/29/54	3.5	(89)	3.7	(94)	3.7	(94)	70	(21)	78	(26)	1.48	5.5	(140)
Vallecito, Calif.	7/18/55	7.1	(180)	6.8	(173)	6.8	(173)	68	(20)	75	(24)	1.41	9.6	(244)
Chiatovich Flat, Calif.	7/19/55	8.25	(219)	6.90	(175)	8.60	(218)	70	(21)	73	(23)	1.16	10.0	(254)
Morgan, Utah	8/16/58	6.75	(171)	6.75	(171)	6.75	(171)	67	(19)	75	(24)	1.48	10.0	(254)
Santa Rita, Ariz.	6/29/59	4.5	(114)	4.5	(114)	4.5	(114)	70	(21)	77	(25)	1.41	6.3	(160)
Elko, Nev.	8/27/70	3.64	(92)	3.64	(92)	3.64	(92)	68	(20)	74	(23)	1.34	4.9	(125)
Bakersfield, Calif.	6/07/72	3.5	(89)	3.1	(79)	3.1	(79)	64	(18)	68	(20)	1.16	3.6	(91)
Phoenix, Ariz.	6/22/72	5.25	(133)	4.57	(116)	4.57	(116)	70	(21)	75	(24)	1.28	5.8	(147)
Encinitas, Calif.	10/12/89*	7.58	(192)	4.00	(101)	4.00	(101)	65	(18)	72	(22)	1.41	5.6	(142)
Wrights, Calif.	9/12/18	3.5++	(89)	3.5	(89)	3.5	(89)	62	(17)	69	(21)	1.41	4.9	(125)
Avalon, Calif.	10/21/41	5.53	(141)	3.50	(89)	3.50	(89)	54	(12)	66	(19)	1.82	6.4	(163)
Newton, Calif.	9/18/59	10.6	(270)	6.5	(165)	6.5	(165)	59	(15)	68	(20)	1.56	10.1	(256)

*Storm date prior to 1900.
**Amount is questionable.
+Based on Phoenix and Grand Junction dewpoints and on estimated dewpoint at Durango determined from minimum temperatures.
++24-hr amount of 8.75 in. (222 mm) reduced to 1-hr approximation by subtracting 24-hr amount at a nearby station.
#Adjustment for elevation made for stations above 5000 ft (1524 m), no adjustment for those below 5000 ft.

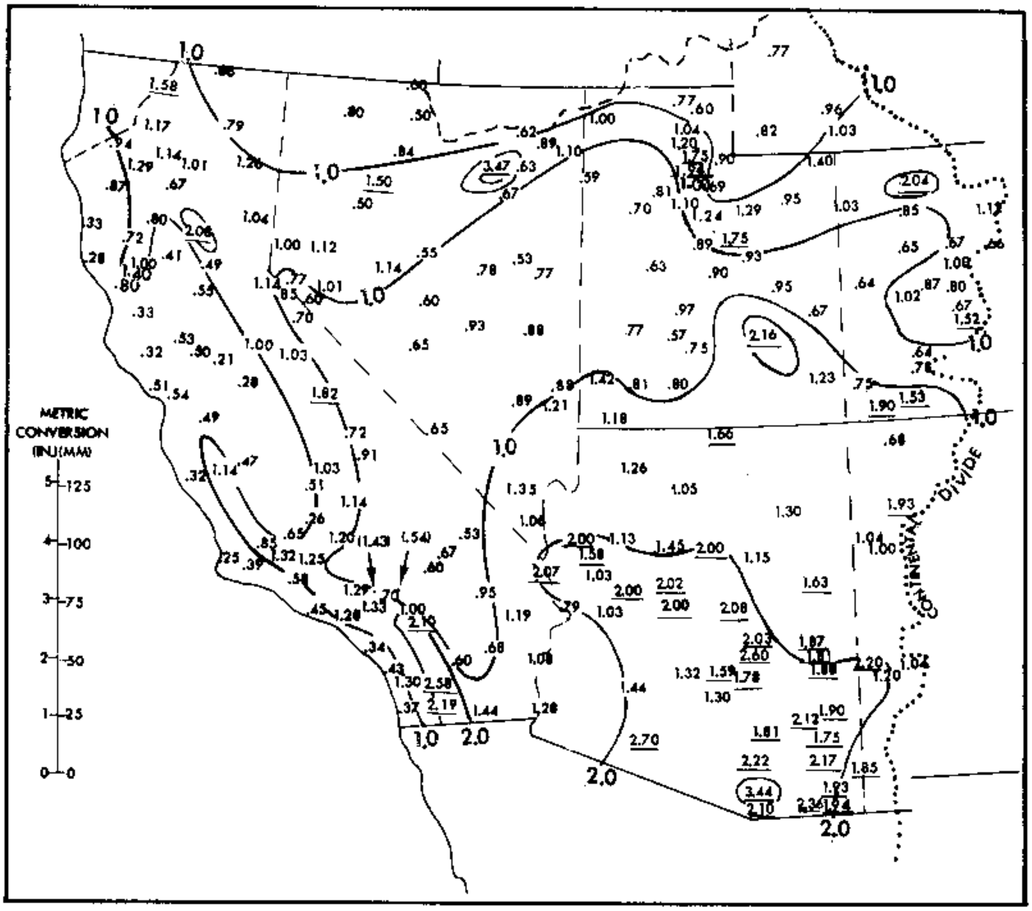

Figure 4.4.--Maximum clock-hour rainfalls at stations with records for period 1940-1972. Underlined values exceed 1.5 inches (38 mm).

The analysis of maximum 1-hr rains in figure 4.4 is a step toward the analysis of the 1-hr PMP in figure 4.5. The primary basis for the 1-hr PMP analysis was the maximized rains in table 4.2, with guidance from the analysis in figure 4.4. Controlling maxima are those at Newton, Chiatovich Flat, Morgan, Ft. Mohave, Avalon, and Campo (underlined on the figure). In addition, maximum moisture and the effects of terrain on the inflow of moisture from source region to storm center was taken into account. The assumption is made that near-maximum moisture necessary to produce a PMP-type event must enter the Southwest from the warm waters of the Gulf of California and the subtropical southeastern Pacific. This assumption is supported by studies of many of the major rainfalls listed in table 4.1. Major terrain barriers obstruct or channelize the inflow of moisture. Figure 4.5 shows a tongue of maximum PMP exceeding 12.0 inches (305 mm) extending northward along the Imperial Valley of southern California. This is part of a broader tongue that penetrates into much of the lower Colorado River drainage and into the Great Basin. It envelops both the Chiatovich Flat, Calif. and Morgan, Utah

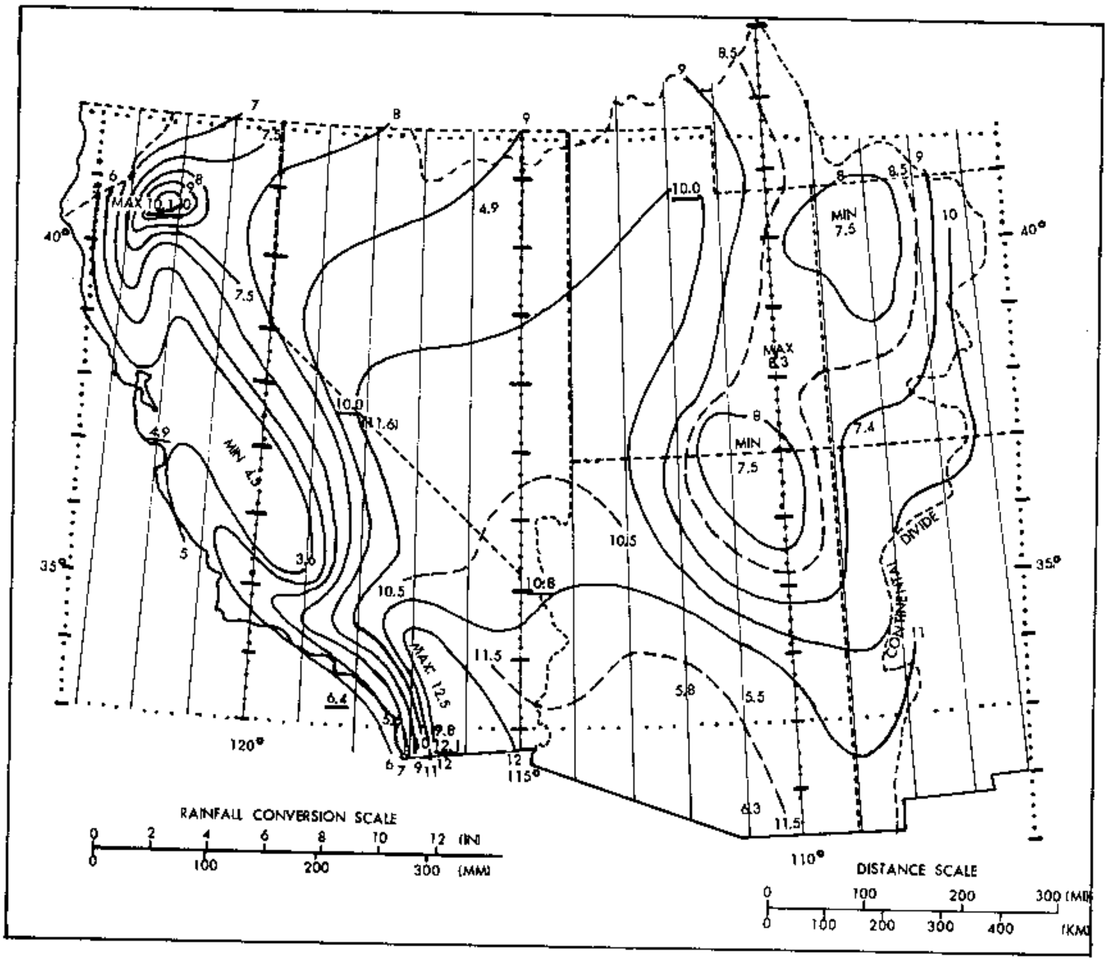

Figure 4.5--Local-storm PMP for 1 mi^2 (2.6 km^2) 1 hr. Directly applicable for locations between sea level and 5000 ft (1524 m). Elevation adjustment must be applied for locations above 5000 ft.

events. In contrast to figure 4.4, figure 4.5 maintains a maximum between these two locations. There is no known meteorological basis for a different solution. The analysis suggests that in the northern portion of the region maximum PMP occurs between the Sierra Nevada on the west and the Wasatch range on the east.

A discrete maximum (> 10 inches, 254 mm) occurs at the north end of the Sacramento Valley in northern California because the northward-flowing moist air is increasingly channeled and forced upslope. Support for this PMP center comes from the Newton, Kennett, and Red Bluff storms (fig. 4.1). Although the analysis in this region appears to be an extension of the broad maximum through the center of the Southwestern Region, it does not indicate the direction of moist inflow. The pattern has evolved primarily as a result of attempts to tie plotted maxima into a reasonable picture while considering inflow directions, terrain effects, and moisture potential.

The last mentioned considerations were important in establishing the gradients through north-central Arizona and the northeastern quadrant of the region of interest. The Mogollon Rim, a range 5,000 to 7,000 feet (1,524 to 2,134 m) in elevation appears to be a prominent obstacle to the low-level moist flows coming northward from the Gulf of California. We believe this barrier is the principle reason why no large local-storm rainfall has been observed to the northeast, and that a sheltering effect is reasonable for the PMP analysis. To the south and southwest of the Mogollon Rim, the PMP increases to a maximum, to reflect the available moisture.

4.4 Durational Variation

4.4.1 Duration of Local-Storm PMP

We postulated that the most extreme or PMP-type local storm could last for 6 hours. A large portion of the total storm should occur in the first hour and almost all within 3 hours. An exception lies in the coastal drainage areas of California where a more continuous inflow of moisture is possible, particularly when synoptic scale systems are involved. Thus, PMP of up to 6 hours probably comes from a moisture resupply that is more typical of the general-storm situation.

4.4.2 Data and Analysis for Durations from 1 to 6 Hours

To obtain local-storm PMP for durations from 1 to 6 hours a number of types of rainfall data were studied. One source of data was recorder station maxima (1940-72). Amounts for 1, 6 and 24 consecutive clock-hour amounts were chosen that met the following conditions.

a. A criterion of minimum clock-hour amounts was established on a regional basis as shown in figure 4.6. The criterion recognizes differences in the magnitude of extremes over the region.

b. The 1-, 6-, and 24-hr consecutive clock-hour amounts at a station must occur on the same date.

c. The 24-hr amount could not exceed the 6-hr amount by more than 0.1 inch (2.5 mm). This helped avoid general type storms.

From data meeting the above criteria, 6/1-hr ratios of rainfall were determined. Averages of ratios for stations within 2° latitude-longitude grid units were used to smooth the data. An analysis of the grid averaged data is shown in figure 4.7.

This analysis needed only slight adjustment to reflect anticipated sheltering influences of major terrain barriers. Especially noteworthy is the strong gradient along the eastern slopes of the Sierra Nevada. East of this gradient the ratios range between 1.10 and 1.40. A zone of minimum ratios (1.10 to 1.20) is centered in the plateau region of southeastern Utah and northeastern Arizona. This minimum can be ascribed to the sheltering effects of the Wasatch range on the west, the Mogollon Rim on the south,

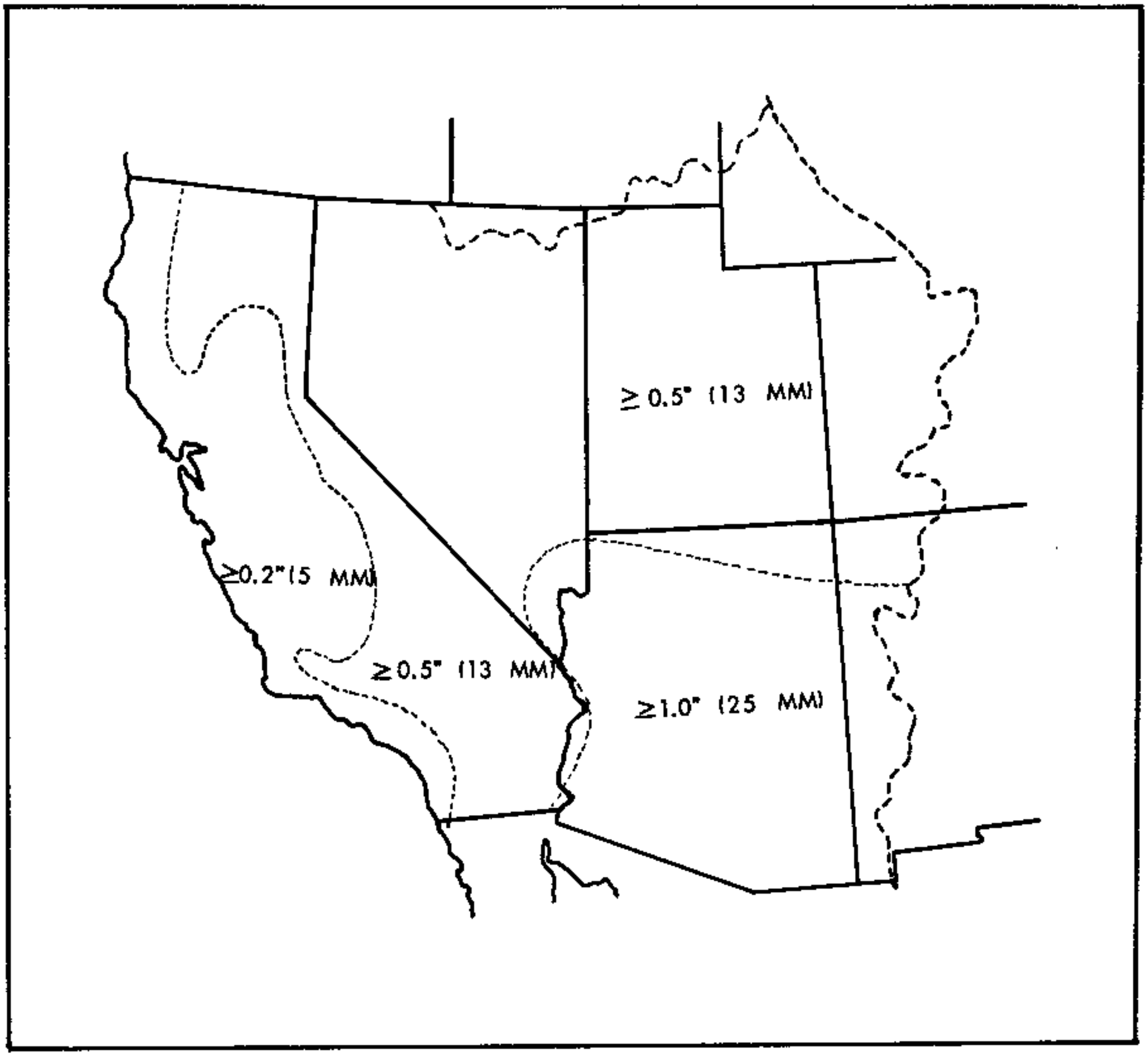

Figure 4.6.--Criteria of clock-hour rainfall amounts used for selection of storms at recorder stations for depth-duration analysis.

and the Rockies on the east. The apparent minimum in Nevada shown by the data is questionable since there are no broadscale topographic features blocking moisture flow. The result may be due to a deficiency of data.

With the exception of the Mojave Desert, the analysis in California shows considerably higher ratios. The maximum along the coast and into the upper Central and Sacramento Valleys exceeds 1.80. Farther inland, terrain barrier effects reduce the ratios.

The wide range of 6/1-hr ratios shown in figure 4.7 suggests that the entire region cannot be represented by a single depth-duration relation. The problem is similar to the depth-duration problem of general-storm PMP (see section 2.4) and we used a similar solution: Find a suitable relation to

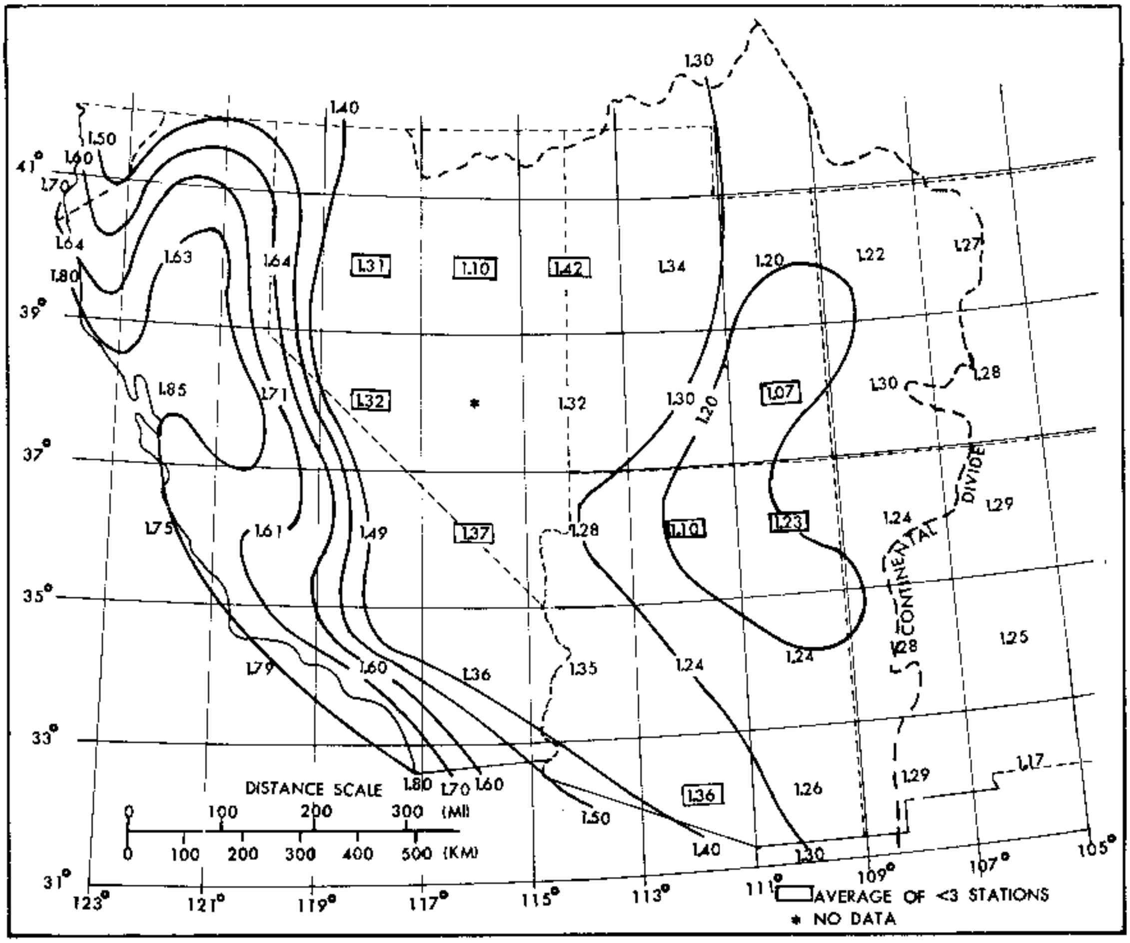

Figure 4.7.--Analysis of 6/1-hr ratios of averaged maximum station data (plotted at midpoints of a 2° latitude-longitude grid).

establish the basic depth-duration curve, then structure a variable set of depth-duration curves to cover the range of 6/1-hr ratios that are needed.

Three sets of data were considered for obtaining a base relation (see table 4.3 for depth-duration data).

a. An average of depth-duration relations from each of 17 greatest 3-hr rains from summer storms (1940-49) in Utah (U. S. Weather Bureau 1951b) and in unpublished tabulations for Nevada and Arizona (1940-63). The 3-hr amounts ranged from 1 to 3 inches (25 to 76 mm) in these events.

b. An average depth-duration relation from 14 of the most extreme short-duration storms listed in Storm Rainfall (U. S. Army, Corps of Engineers 1945-). These storms come from Eastern and Central States and have 3-hr amounts of 5 to 22 inches (127 to 559 mm).

Table 4.3.--Depth-duration relations of severe local storms

	Duration (hr)			
	1	2	3	6
	Percent of 1-hr value			
1. Average of 17 storms Utah, Nevada, and Arizona (recorder data)	100	125	133	152
2. Average of 14 most extreme short-duration storms in Storm Rainfall (U. S. Corps of Engineers 1945-)	100	125	135	166
3. March 3, 1945, Los Angeles storm (U. S. Corps of Engineers 1958)	100	118	128	(144)

c. The depth-duration variation from one of the best documented thunderstorm rainfalls of record in the Southwest. This is the 3-hr, 3.3-in. (84-mm) fall in Los Angeles County, Calif. on March 3, 1943 (U. S. Army, Corps of Engineers 1958). Even though this rainfall was imbedded in more general storm rains, March 3-6, 1943, covering parts of several states, the large amount of reliable data for the event make it useful.

Most of the extreme local storms in the study region (table 4.1) lasted less than 3 hours and little depth-duration data are available for them. We would expect that a representative PMP depth-duration curve would have a lower 6/1-hr ratio than either of the first relations listed. We chose to adopt the relation for the March 3, 1943 storm as guidance for the basic depth-duration curve for the local-storm PMP. A smooth extension of this relation to 6 hours gave a 6-hr value that is 144% of the 1-hr amount. This relation is quite similar to the local storm depth-duration curve of HMR No. 43 in which major Southwest storms were considered. For a variable relation, a family of curves (fig. 4.3) was established where the 6-hr values were incrementally 10% greater than the 1-hr amount. A smooth curve was drawn between the 1-hr (100%) point and the 6-hr (110%) point. The remaining curves were determined by the ratio of the 6-hr value to the difference between 110% and the basic depth-duration (dashed line fig. 4.3) curve.

4.4.3 Data and Analysis for Less Than 1-Hr Duration

Durational relationships for durations less than 1 hour were obtained from data at first-order stations in Utah, Arizona, Nevada and southern California for a period of record between 1954 and 1970. Tables of excessive precipitation at these stations are summarized in the Annual Summary of Climatological Data (U. S. Weather Bureau 1954-) for durations of 5 to 180 minutes. These data showed that storms with low 3/1-hr rain ratios had higher 15-min to 1-hr ratios than storms with high 3/1-hr ratios. The geographical distribution of 15-min to 1-hr ratios also were inversely correlated with magnitudes of the 6/1-hr ratios of figure 4.7. For example, Los Angeles and San Diego (high 6/1-hr ratios) have low 15-min to 1-hr ratios (approximately 0.60) whereas the 15-min to 1-hr ratios in Arizona and Utah (low 6/1-hr ratios) were generally higher (approximately 0.75).

Depth-duration relations for durations less than 1 hour were then smoothed to provide a family of curves consistent with the relations determined for 1 to 6 hours, as shown in figure 4.3. Adjustment was necessary to some of the curves to provide smoother relations through the common point at 1 hour.

We believe we were justified in reducing the number of the curves shown in figure 4.3 for durations less than 1 hour, letting one curve apply to a range of 6/1-hr ratios. The corresponding curves have been indicated by letter designators, A-D, on figure 4.3. As an example, for any 6-hr amount between 115% and 135% of 1-hr, 1-mi^2 (2.6-km^2) PMP, the associated values for durations less than 1 hour are obtained from the curve designated as "B".

Table 4.4 lists durational variations in percent of 1-hr PMP for selected 6/1-hr rain ratios. These values were interpolated from figure 4.3.

To determine 6-hr PMP for a basin, use figure 4.3 (or table 4.4) and the geographical distribution of 6/1-hr ratios given in figure 4.7.

Table 4.4.--Durational variation of 1-mi^2 (2.6-km^2) local-storm PMP in percent of 1-hr PMP (see figure 4.3)

6/1-hr	Duration (hr)								
ratio	1/4	1/2	3/4	1	2	3	4	5	6
1.1	86	93	97	100	107	109	110	110	110
1.2	74	89	95	100	110	115	118	119	120
1.3	74	89	95	100	114	121	125	128	130
1.4	63	83	93	100	118	126	132	137	140
1.5	63	83	93	100	121	132	140	145	150
1.6	43	70	87	100	124	138	147	154	160
1.8	43	70	87	100	130	149	161	171	180
2.0	43	70	87	100	137	161	175	188	200

4.5 Depth-Area Relation

We have thus far developed local-storm PMP for an area of 1 mi^2 (2.6 km^2). To apply PMP to a basin, we need to determine how 1-mi^2 (2.6-km^2) PMP should decrease with increasing area. We have adopted depth-area relations based on rainfalls in the Southwest and from consideration of a model thunderstorm.

Figure 4.8 is a plot of available depth-area data for major local storms listed in table 4.1. The durations given with the 7 storms are longer than for the point value because of the areal pattern. Most of the data from which areal patterns were drawn came from bucket surveys and other unofficial observations.

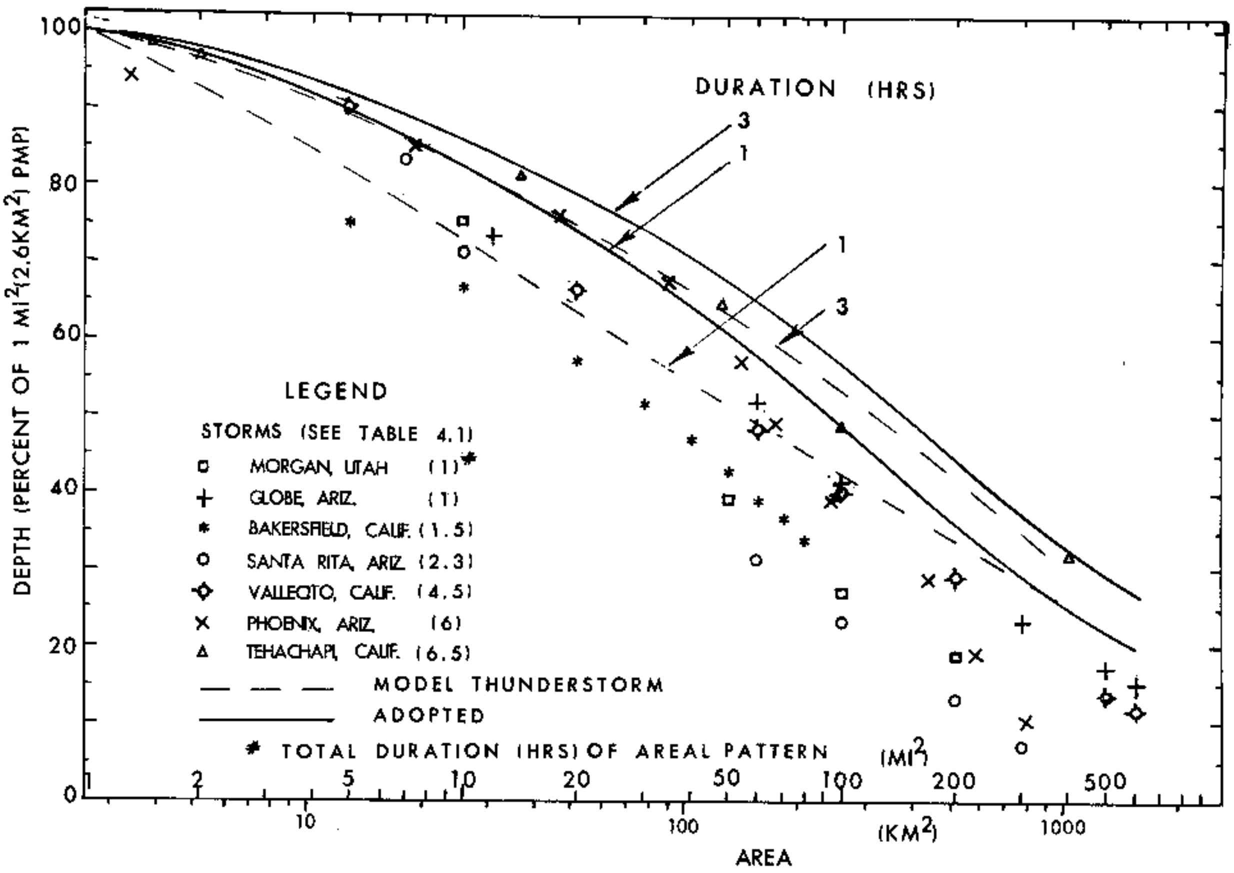

Figure 4.8.--Depth-area relations adopted for local-storm PMP in the Southwest and other data.

Also shown on figure 4.8 are 1- and 3-hr curves from a model thunderstorm. The following conditions comprised the model:

a. A depth-duration relation for 1 mi^2 (2.6 km^2) based on a 6-hr percent of 1 hr of 144% (fig. 4.3).

b. Circular isohyets.

c. A storm rate of travel of 4 mph (1.8 m/sec).

d. A rate of change in storm intensity due to storm motion the same throughout the areal pattern as at a point.

Both the data and the model thunderstorm results were used in determining the adopted depth-area relations for 1 and 3 hours shown on figure 4.8. A first consideration is that the relation must envelop the data. The adopted 1-hr curve shown in figure 4.8 envelops the 1-hr rains (Globe, Morgan and Bakersfield) by roughly 10%. Only data for the two 6-hr rains (Phoenix and Tehachapi) exceed the 1-hr curve. The adopted 3-hr curve envelops all the storm data. The model thunderstorm curves are also enveloped. In the model thunderstorm we assume that if the rate of travel were reduced, the model curves would approach the adopted curves.

A depth-area curve for the Southwest for 6 hours was estimated from relations given in HMR No. 43 based on selected storms for the Eastern United States. Using the curves for 1-, 3-, and 6-hr durations, relations were interpolated for intermediate durations. Depth-duration curves based on these relations and for a number of area sizes were used to obtain values to approximate curves for durations less than 1 hour. The adopted depth-area relations are shown in figure 4.9.

4.6 Distribution of PMP Within a Basin

Idealized elliptically shaped isohyets patterned after the few available storms have been developed for distribution of PMP. The extreme storms at Globe and Vallecito were examples from which an isohyetal pattern having a 2:1 axial ratio was adopted for application throughout the Southwest. The pattern, shown in figure 4.10, is drawn to a 1:500,000 scale. Isohyets are shown on this idealized pattern labeled A (1 mi^2, 2.6 km^2) to J (500 mi^2, 1,295 km^2).

Table 4.5 gives isohyets labeled in percent of 1-hr 1-mi^2 (2.6-km^2) PMP for the 4 highest 15-min incremental PMP values. Incremental labels are given for each of the four indexed 6/1-hr ratio categories (see fig. 4.3). These labels when multiplied by the 1-hr 1-mi^2 (2.6-km^2) PMP for a specific drainage give drainage PMP isohyetal labels for the 4 highest 15-min increments. Table 4.5 also gives isohyetal labels for 1-hr PMP. The resulting isohyetal values take into account the depth-duration relations of figure 4.9.

For obtaining PMP out to 6 hours duration (remaining five lesser 1-hr increments of PMP), use the isohyetal values given in table 4.6. The 1-hr increments of PMP are listed in successively decreasing order of magnitude. The percents by which the 1-hr 1-mi^2 (2.6-km^2) PMP are to be multiplied to obtain isohyetal values are categorized by the 6/1-hr ratios. Steps outlining the application of these percents are presented along with an example in chapter 6.

4.7 Time Distribution of Incremental PMP

We have little information about the time sequence of incremental 1-hr rainfalls for intense local storms. A study of sequences of increments in each of 38 six-hr storms (U. S. Weather Bureau 1947) resulted in an average mass curve in which the maximum intensities occurred in the middle of the

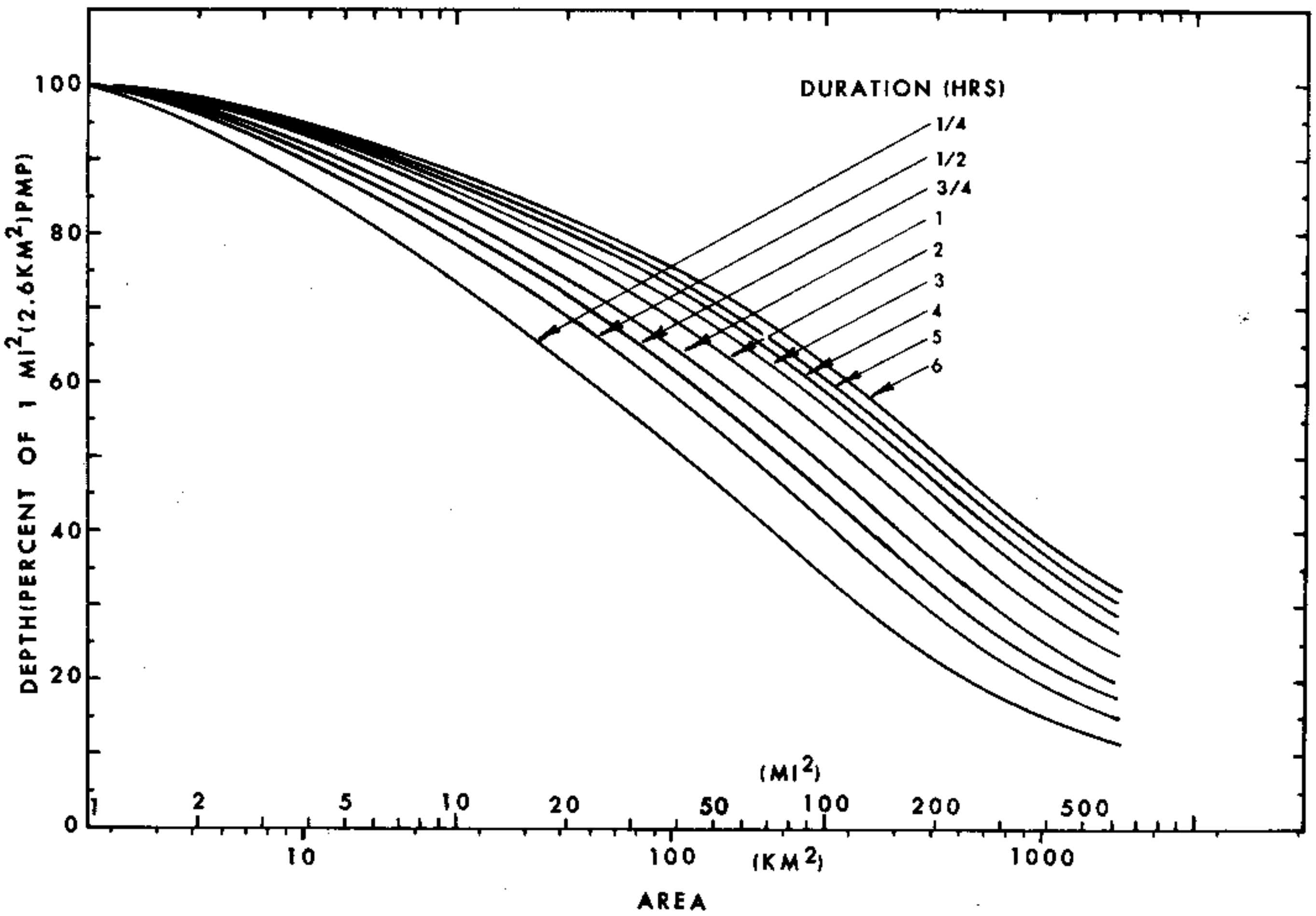

Figure 4.9.--Adopted depth-area relations for local-storm PMP.

Table 4.5.--Isohyetal labels for the 4 highest 15-min PMP increments and for 1-hr PMP

6/hr ratio (%)	PMP Increment	A	B	C	D	E	F	G	H	I	J
		Enclosed area mi^2 (km^2)									
		1 (2.6)	5 (13)	25 (65)	55 (142)	95 (246)	150 (388)	220 (570)	300 (777)	385 (997)	500 (1,295)
		Percent of 1-hr, 1-mi^2 (2.6-km^2) PMP									
<115 (A)	Highest 15-min.	86	68	44	30	18	10	7	6	5	4
	2nd. 15-min.	7	7	7	7	7	6	4	3	3	3
	3rd. 15-min.	4	4	4	4	4	4	3	2	2	2
	4th. 15-min.	3	3	3	3	3	3	2	2	2	2
116-135 (B)	Highest 15-min.	74	56	32	21	14	8	7	6	5	4
	2nd. 15-min.	15	15	15	12	9	6	4	3	3	3
	3rd. 15-min.	6	6	6	6	5	5	3	2	2	2
	4th. 15-min.	5	5	5	5	4	4	2	2	2	2
136-155 (C)	Highest 15-min.	63	45	27	18	11	7	6	5	4	4
	2nd. 15-min.	20	20	15	12	9	6	4	3	3	3
	3rd. 15-min.	10	10	9	8	7	5	3	3	3	3
	4th. 15-min.	7	7	7	6	5	5	3	2	2	2
>156 (D)	Highest 15-min.	43	31	19	14	9	7	5	4	4	4
	2nd. 15-min.	27	23	16	12	8	6	4	3	3	3
	3rd. 15-min.	17	16	13	10	8	5	4	3	3	2
	4th. 15-min.	13	12	10	8	7	5	3	3	2	2
	1-hr.PMP	100	82	58	44	32	23	16	13	12	11

Table 4.6.--Isohyetal labels for second to sixth hourly incremental PMP in perceont of 1-hr 1-mi^2 (2.6-km^2) PMP

6/1-hr ratio	Isohyet A	B	C	D	E	F	G	H	I	J
				Second highest 1-hr PMP increment						
1.1	7	7	7	7	7	7	6	4	4	4
1.2	11	11	11	11	10	8	7	5	5	5
1.3	14	14	14	12	11	9	7	5	5	5
1.4	17	17	16	14	12	10	8	6	6	6
1.5	21	20	18	16	13	11	8	6	6	6
1.6	24	23	20	18	15	12	9	7	7	6
1.7	27	26	23	20	16	13	10	7	7	7
1.8	30	29	25	21	17	14	10	8	8	7
1.9	34	32	27	23	18	14	11	8	8	8
				Third highest 1-hr PMP increment						
1.1	2	2	2	2	2	2	2	2	2	2
1.2	4	4	4	4	4	4	4	4	4	4
1.3	6	6	6	6	6	6	5	5	5	5
1.4	9	9	9	9	8	7	6	5	5	5
1.5	11	11	11	11	10	8	7	5	5	5
1.6	14	14	14	13	11	10	8	6	6	6
1.7	17	17	17	14	13	11	8	7	6	6
1.8	19	19	18	16	14	12	9	7	6	6
1.9	21	21	20	18	15	13	10	8	7	7
				Fourth highest 1-hr PMP increment						
1.1	1	1	1	1	1	1	1	1	1	1
1.2	3	3	3	3	3	3	3	3	3	3
1.3	5	5	5	5	5	5	5	4	4	4
1.4	6	6	6	6	6	5	5	4	4	4
1.5	7	7	7	7	7	6	5	4	4	4
1.6	8	8	8	8	7	6	5	5	5	5
1.7	10	10	10	9	8	7	6	5	5	5
1.8	12	11	11	10	9	8	7	6	5	5
1.9	14	13	12	11	10	9	7	6	6	6
				Fifth highest 1-hr PMP increment						
1.1	1	1	1	1	1	1	1	1	1	1
1.2	2	2	2	2	2	2	2	2	2	2
1.3	3	3	3	3	3	3	3	3	3	3
1.4	5	5	5	5	5	5	4	4	4	4
1.5	6	6	6	6	6	5	5	4	4	4
1.6	7	7	7	7	7	6	5	5	5	5
1.7	9	9	9	9	8	7	5	5	5	5
1.8	10	10	10	10	9	7	6	6	5	5
1.9	12	12	12	11	9	8	6	6	6	6
				Sixth highest 1-hr PMP increment						
1.1	1	1	1	1	1	1	1	1	1	1
1.2	1	1	1	1	1	1	1	1	1	1
1.3	2	2	2	2	2	2	2	2	2	2
1.4	4	4	4	4	4	4	4	4	4	3
1.5	5	5	5	5	5	5	4	4	4	4
1.6	6	6	6	6	6	5	5	5	5	5
1.7	7	7	7	7	7	6	5	5	5	5
1.8	8	8	8	8	8	6	5	5	5	5
1.9	9	9	9	9	9	8	6	6	5	5

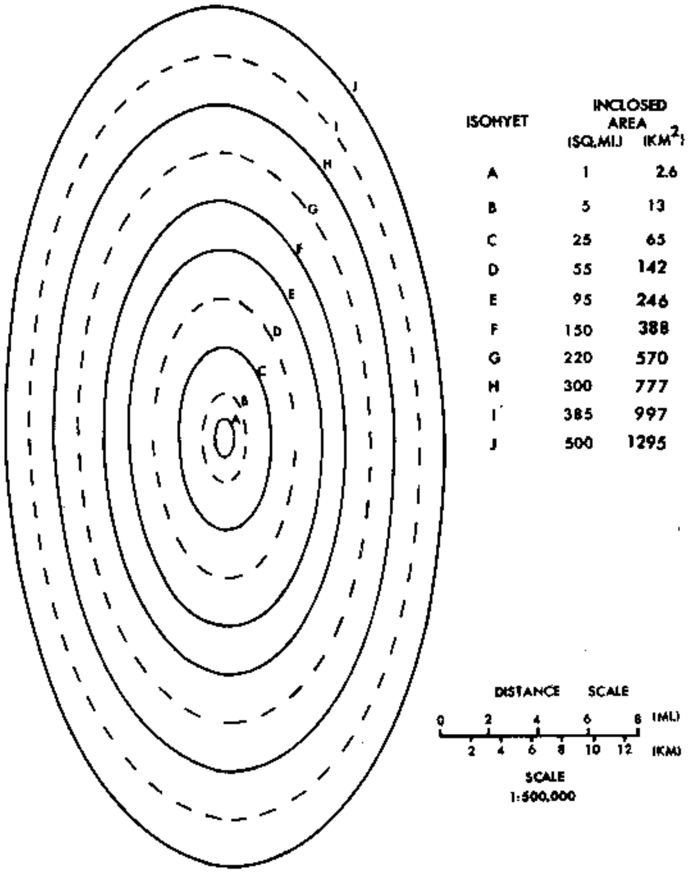

Figure 4.10.--Idealized local-storm isohyetal pattern.

storm period. The sequence of hourly incremental PMP for the Southwest 6-hr thunderstorm in accord with this study is presented in column 2 of table 4.7. A small variation from this sequence is given in Engineering Manual 1110-2-1411 (U. S. Army, Corps of Engineers 1965). The latter, listed in column 3 of table 4.7, places greater incremental amounts somewhat more toward the end of the 6-hr storm period. In application, the choice of either of these distributions is left to the user since one may prove to be more critical in a specific case than the other.

Table 4.7.--Time sequence for hourly incremental PMP in 6-hr storm

	HMR No. 5[1]	EM1110-2-1411[2]
Increment	Sequence Position	
Largest hourly amount	Third	Fourth
2nd largest	Fourth	Third
3rd largest	Second	Fifth
4th largest	Fifth	Second
5th largest	First	Last
least	Last	First

[1]U. S. Weather Bureau 1947.
[2]U. S. Corps of Engineers 1952.

Also of importance is the sequence of the four 15-min incremental PMP values. We recommend a time distribution, table 4.8, giving the greatest intensity in the first 15-min interval (U.S. Weather Bureau 1947). This is based on data from a broad geographical region. Additional support for this time distribution is found in the reports of specific storms by Keppell (1963) and Osborn and Renard (1969).

Table 4.8.--Time sequence for 15-min incremental PMP within 1 hr.

Increment	Sequence Position
Largest 15-min amount	First
2nd largest	Second
3rd largest	Third
least	Last

4.8 Seasonal Distribution

The time of the year when local-storm PMP is most likely is of interest. Guidance was obtained from analysis of the distribution of maximum 1-hr thunderstorm events through the warm season at the recording stations in Utah, Arizona, and in southern California (south of 37°N and east of the Sierra Nevada ridgeline). The period of record used was for 1940-72 with an average record length for the stations considered of 27 years. The month with the one greatest thunderstorm rainfall for the period of record at each station was noted. The totals of these events for each month, by States, are shown in table 4.9.

Table 4.9.--Seasonal distribution of thunderstorm rainfalls.

(The maximum event at each of 108 stations, period of record 1940-72.)

	Month						
	M	J	J	A	S	O	No. of Cases
Utah	1	5	9	14	5		34
Arizona		4	16	19	4		43
S. Calif.*		14	10	7			31
No. of cases/mo.	1	23	35	40	9	0	

*South of 37°N and east of Sierra Nevada ridgeline.

This distribution, by months, agrees well with the month of occurrence of the extreme thunderstorm rainfalls for the Southwest listed in table 4.1. July and August have the greatest frequency of extreme rains in both sets of data.

For the coastal drainages of California, most thunderstorms are associated with general-storm rainfalls (see discussion in the companion volume, Schwarz and Hansen 1978). The occurrence of these cool-season mid-latitude and tropical storm systems is apparently limited to the spring and fall months. Figure 4.11 presents the regional variation of the months of greatest potential for a 1-hr thunderstorm event approaching the magnitude of PMP.

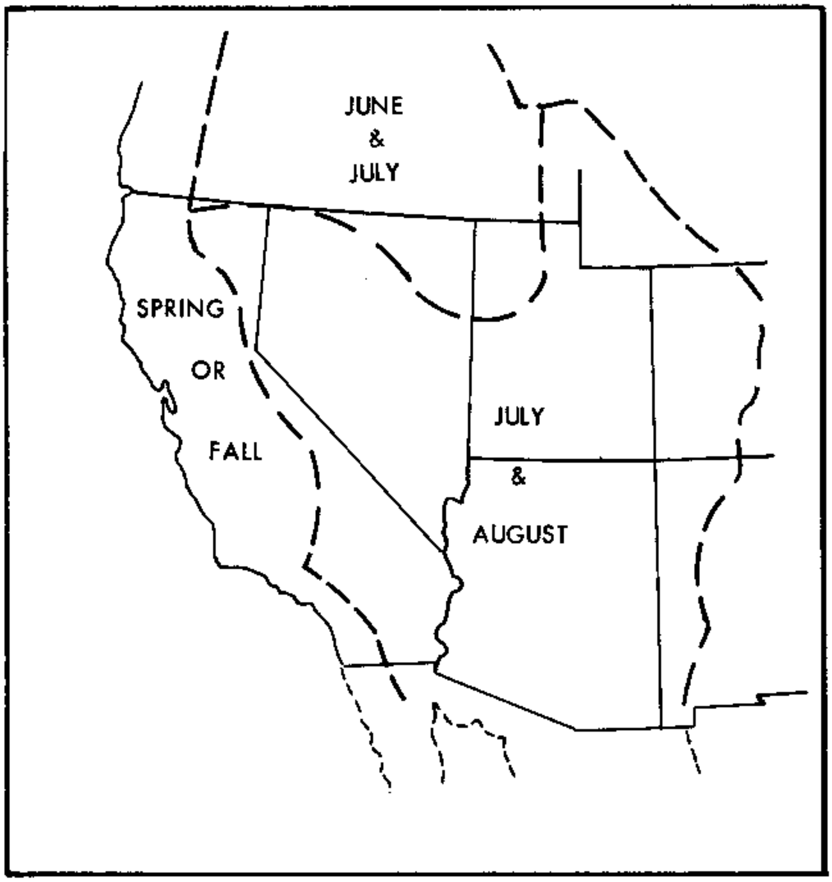

Figure 4.11.--Regional variation of month of maximum local-storm rainfall. (boundaries are not precise)